AD NUMBER
ADA492034
CLASSIFICATION CHANGES
TO: **UNCLASSIFIED**
FROM: **RESTRICTED**
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to DoD only; Administrative/Operational Use; APR 1965. Other requests shall be referred to British Embassy, 3100 Massachusetts Avenue, NW, Washington, DC 20008.**
AUTHORITY
DSTL ltr dtd 12 Dec 2006; DSTL ltr dtd 12 Dec 2006

7/65

~~CONFIDENTIAL~~

COPY No. 102

ROYAL

ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT

EXPLOSIVES DIVISION

R.A.R.D.E. MEMORANDUM 7/65

The physics and statistics of the electrical initiation process in conducting composition systems

J. W. Martin

Fort Halstead
Kent.

April,
1965

R.A.R.D.E.
Printing Section

ROYAL ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT

R.A.R.D.E. MEMORANDUM 7/65

The physics and statistics of the electrical initiation process in conducting composition systems

J. W. Martin (E1)

Summary

The resistance of a random array of a mixture of conducting and explosive particles is studied using a Monte Carlo approach and a combination of digital and analog computing. Voltage sensitivity is discussed using the maximum current concentrations in the array, electric contact theory and the hot spot theory of thermal explosion. It is considered that 2 volts is the threshold for safety in graphite devices and that above two volts there are several distinct mechanisms for energy transfer from conductor to the explosive. At 4 volts the contacts disrupt giving efficient energy transfer by impact of incandescent vapour. This is considered to be the mechanism of the fast mode of action used in Service devices.

Approved for issue:

S.W. Coppock, Principal Superintendent, 'E' Division

CONTENTS

IMPORTANT

This document should be returned to the Reports Officer, Royal Armament Research and Development Establishment, Fort Halstead, Sevenoaks, Kent. when no longer required

INITIAL DISTRIBUTION

Internal

No. 1	Director	
2	Deputy Director	
3	SMO	
4	PS/E	
5	PS/A	
6	PS/B	
7	PS/C	
8	PS/D	
9	Dr.W.M.Evans	
10	SNO	
11	SAFO	
12	MPC(A)&(C)	
13	MPC(B)	
14	S/E1	
15	S/A1	
16	S/A2	
17	S/A3	
18	S/B3	
19	S/B4	
20	S/C1	
21	S/C2	
22	S/C3	
23	S/D1	
24	S/E3	
25-31	E1	(Att.Dr.F.E.Ball, Mr.N.Griffiths, Mr.W.S.Hall, Mr.R.C.Harris, Dr.E.A.Hutton, Mr.J.W. Martin, Mr.W.Scamaton)
32	A1	(Att. Mr.J.Saunders)
33-35	A3	(Att.Mr.K.G.Anderson, Cdr,P.J.Jenner,RN, Mr.A.R.Snelling)
36-37	B3	(Att.Mr.G.R.R.Bray, Mr.W.A.Sutherland)
38-39	B4	(Att.Mr.A.W.Duneclift, Mr.P.R.Layton)
40-43	C2	(Att.Mr.R.A.Dawe, Mr.J.Fettes, Dr.R.Rosser,Dr.A.G.Walters)
44-45	C3	(Att.Mr.P.J.Deas, Mr.D.Harvey)
46	D1	(Att.Mr.A.Cornish)
47	E3	(Att.Mr.G.A.P.N.Barlow)

External (UK)

No. 48	Chief Scientist, M of A
49	Chief Scientist (Army)
50	Deputy Chief Scientist (Army)
51	D.G. of Arty/Admin
52	D of Arty (R & D)
53	DAP(A), Main Bldg. Whitehall
54	Commdt.RMCS, Shrivenham,Swindon,Wilts.
55	CS/A & AEE, M of A, Boscombe Down,Salisbury,Wilts.
56	CS/ASWE,Navy Dept., Portsdown, Cosham, Hants.
57	- (Att.Mr.E.J.W.Underhill)
58	CS/NDUWE, Navy Dept., Portland, Dorset.
59	CSO, M of A, Adelphi, John Adam St., London W.C.2.
60	CSR,Charles House, Kensignton High St., London W.14.
61	D A Arm, M of A, St.Giles Court
62	- (Att.Mr.F.Greenwood)
63	D/ERDE, M of A, Waltham Abbey, Essex
64-67	- (Att.Dr.A.Lovecy, Mr.G.W.C.Taylor, Mr.A.T.Thomas, Dr.R.M.H.Wyatt)
68	D/FVRDE, Chobham Lane, Chertsey, Surrey
69	- (Att.Mr.J.E.Lay)
70	DGA(N), Old Admiralty Bldg.,Whitehall, S.W.1.
71	DG/GW, M of A, Castlewood House
72	DGW(I), Navy Dept. Bath, Somerset.
73-75	- (Att.Cdr.D.R.Beatty, RN, Cdr.W.D.Moseley, RN, Cdr.F.W.Walbonicke, RN)
76	DGW(N), M of A, Castlewood House
77	DGW(S), Navy Dept., Bath, Somerset.
78	- (Att.Cdr R.J.S.Hobbs, RN)
79	D/RAE, Farnborough, Hants.
80-82	- (Att. Mr.H.Drysdale, Mr.F.A.Green, Mr.C.E.White)
83	DSS, Lansdowne House, Berkeley Sq., London, W.1.
84	DRNAD Navy Dept., Ernesettle, Plymouth, Devon.
85	GW(G&C)5, M of A, Castlewood House
86	GW(P&W)1, M of A, Castlewood House (Att.Mr.D.M.Wilcox)
87	GW(P&W)5, M of A, Castlewood House (Att.W/Cdr.R.J.Edmonds)
88	RAE,Aberporth, Cardiganshire
89	RAF/B2, M of A, St.Giles Court
90	Secretary, OB
91	- (Att. Chairman E/E Hazards Committee)
92	Army Department Branch Library, St.Christopher House
93-94	TIL - for retention

Overseas (through TIL)

95	BDSW(R&D) (Att.Director of Munitions)

Stock

96-105

1. INTRODUCTION

Electrical initiators of a type known as conducting composition have been in use for many years. They consist of a mixture of explosive and conducting powders filled into a casing containing electrodes which make contact with the conducting composition. These devices are remarkably flexible in being suitable for many initiating systems. Perhaps their principle advantage is the very fast functioning time, which is easily achieved. Another advantage is the range of application ranging from sensitive devices firing on a few microjoules to very insensitive systems which will dissipate steadily many watts. They are also shock resistant and behave well in extremes of climate.

In this country conducting compositions have superior characteristics to the early graphite bridge devices and the latter are now obselete. In the U.S., however, wire bridge devices are used in many of the applications where the U.K. use conducting compositions; in the applications requiring the highest levels of sensitivity, however, the graphite bridge fuseheads are still in use.

The mechanism of the initiation in graphite bridge devices is thought to resemble the mechanism now considered to be operative in c.c. devices.

Over a period of many years the technology of these devices has been developed to a fine art and a qualitative understanding of the influence of various parameters such as choice of explosive, conductant and electrode system has been established. An understanding of the mechanism of firing and the type of distribution found in resistance and energy-to-fire has been obtained only in the last few years; a point has now been reached when the reasons for some of the more puzzling aspects of conducting compositions are understood. Given the electrical, thermal and optical properties of conductant A and explosive B, their proportions, size distributions and electrode assembly, it is still not possible to calculate the properties of the product exactly; but the physical basis is now sufficiently understood to allow a calculation to be made as to the order of magnitude of the firing threshold and to explain the distribution properties in geometrical terms.

This recent progress has been aided by a Sub-Committee of the High Explosives Committee of the Scientific Advisory Council formed to study the mechanism of functioning of conducting compositions. At one stage in their studies it was suggested that the resistance and current concentration properties that arose in a simple mathematical model of a conducting composition system should be studied to see if the distributions of resistance and firing energy were reasonably well explained by random geometry of conducting and non-conducting particles in rectangular array.

This problem, even based upon such a simple model, was not as simple as the basic assumptions required to set up the model. However, by a combination of digital and analog computing the solutions have been obtained.

The digital generation of the random arrays was carried out by H.J. Gawlik of D1 Branch (Ref.1) and the analog evaluation of the current concentrations and

measurement of resistance was carried out by Professor S.C. Redshaw at the University of Birmingham (Ref. 2). This work was kept unclassified in view of the possible applications of the results to a wider range of "maze" problems. In this memorandum the results are applied to the original explosive problem.

2. THE MODEL AND ITS DIMENSIONAL COMPARISON WITH THE IGNITER

One of the most useful conducting composition devices is the N8 type igniter, Fig. 1. (This has cylindrical electrodes spaced by a thin anular insulating washer, about .007" thick.) If a current is passed through a conducting filling in this igniter, the current is concentrated in the region of the electrode gap. A chain of particles bridging the electrode gap has a low path length and concentrates the current in that region. Chains from parts of the electrodes distant from the gap would carry very little current owing to their long length and high resistance. The longer chains are also less likely to exist since the probability of obtaining particles in the corrent position to form chains decreases rapidly with chain length. For instance, assuming the chance of having two particles in contact is P. P being quite small, certainly below 0.1, the probability of completing a chain decreases by at least an order of 10 for each extra "link". This is in essence equivalent to two annular electrodes spaced by a thin insulating washer about 0.007 inches thick. In an elementary model it seems justifiable, therefore, to consider only the region of the electrode gap.

The particle size of the ingredients is important in conducting compositions. The explosive is specially prepared in a crystalline form having good pouring properties. The conducting medium is usually fine graphite of particle size about 7 microns and of low bulk density. This fits in between the crystals of explosive in the pressed filling. The average particle size of the explosive ingredient is about 26 microns, giving about seven particles across the electrode gap and about 400 round the periphery in the case of the N8 igniter body.

The simplest possible theoretical model consists of a single plane array of equi-sized conducting and non-conducting particles arranged at random between two parallel electrodes. Where the conducting particles touch there is a contact resistance which is large compared with the bulk resistance of the particle. It is considered possible, at the moment, to extend the simple model to three dimensions and keep the problem within the bounds of computers available at present. An attempt to account for variation of particle sizes, inclusion of random packing and so on, which would be very desirable, leads to enormous complexity for computer solution even though the basic physical picture is clear enough.

The random array 400 particles along the electrodes and seven deep, in the standard case, corresponding approximately to the N8 igniter, has been used with various percentages of conductor to investigate the resistance and sensitivity distributions. The effect of electrode width and length has also been investigated with a hope of suggesting ways of improving reproducibility. This simple model was indeed worth studying and has shown that the geometry of

random arrays accounts largely for the properties of conducting compositions.

3. RESISTANCE

For convenience in analogue computation resistance between particles in contact was taken nominally at 100Ω. This value is of course arbitrary, and may be scaled for comparison with a real conducting composition system if the actual contact resistance is known.

The resistance of conducting composition igniters has already been studied experimentally as a function of the percentage of conductor present and the following relationships have been established:-

(a) The logarithms of the resistance of a batch is normally distributed Fig. 13, 16.

(b) The percentage graphite is linearly related to the reciprocal of the mean logarithm of the resistance. Fig. 14, Fig. 11.

The resistance and percentage conductor relationship is the same for the model as for the N8 igniter, except for the percentage of conductant needed. Whereas in the igniter only about three per cent graphite (by weight) is required to obtain conducting paths in the model about ten times as much is required (by volume). The difference in densities between styphnate and graphite would reduce this to a factor of about six. The main difference is that in the model the particles are of equal size whereas in the N8 igniter the graphite is typically one third the size of the styphnate and of course has a size distribution so that some particles occur even below one micron in diameter. The three dimensional effect will also account for some of this discrepancy.

The distribution of resistance, however, is found to resembled closely the log-normal resistance distribution, typical of c.c. devices Fig. 2. The standard "chi-squared" test of statistics gave a value of 4.7 with five degrees of freedom using a sample of 53, suggesting that the log-normal fit is satisfactory.

From experimental observation the standard deviation of the resistance degreases as the graphite content is increased. The model behaves in the same way as the conducting compositions and this method of reducing resistance variation has already been applied to the 1Ω N8 and 1Ω primer cap, both of which have only about ± 20% total resistance spread.

Figure 18 shows the effect of electrode gap variation. The model suggests that the resistance is very sensitive to electrode gap but that the standard deviation of resistance is not much affected. Changing the electrode gap appears to be a way of controlling the resistance as an alternative to graphite content provided the sensitivity effects are also acceptable. No data on the effect of electrode gap on the resistance and sensitivity are recorded for c.c. devices.

It is probable, in view of the extreme sensitiveness of resistance to electrode gap, that attention to close control of gap size in production will help to keep the resistance spread down. Experience with igniter bodies assembled from incorrectly machined components suggests that the sensitivity spread is adversely affected.

The radius of the contact between spheres pressed together with a force F is given by a formula of Hertz(Gesammelte Werke 1 Leipzig Barth 1895.) If the particles have radius A, Young's modulus E and Poissons ratio 0.3 the radius a, of the contact circle is:-

$$a = 1.1 \left(\frac{F\ A}{2\ E}\right)^{\frac{1}{3}} \qquad 1$$

Suppose now that the powder is under pressure P then $F = \Pi A^2 P$

and $$a = 1.1A \left(\frac{\Pi\ P}{2\ E}\right)^{\frac{1}{3}} \qquad 2$$

By considering the flow through the constriction where particles touch the resistance is $R = \rho/4a$ where ρ is the bulk resistivity (ref. 4 and 6). We may deduce an approximate value of resistance as follows:- For a 26 micron particle $A = 13\mu$, E may be between 1 and 16×10^{-6} from various sources of data on graphite, the higher values being more appropriate for single crystals). A value of about 8×10^{-6} p.s.i. is taken as probable. P is 20,000 p.s.i. in the N8 igniter.

Thus $$a = 1.1 \times 13 \left(\frac{\Pi}{2} \times \frac{20{,}000}{8 \times 10^{-6}}\right)^{\frac{1}{3}} \text{ microns} = 4.4 \text{ microns}$$

and $$R = \frac{8 \times 10^{-3}}{4 \times 4.4 \times 10^{-4}} = 4.5 \text{ ohms}$$

This value is surprisingly low, However, with the finer graphites the contact resistance will increase inversely with particle size and the overall resistance inversely as the square of the particle size, more particles being required to bridge the electrode gap. The resistance per contact is not sensitive to pressure or Young's modulus and the high values of resistance found in practice could be accounted for by an increase in ρ but more likely by the assumption that the styphnate matrix carries most of the load, the graphite being in lighter contact in the interstices.

4. SENSITIVITY

In order to assess the meaning of sensitivity as derived from the model it is necessary to introduce the physical concepts underlying the theory of the mechanism by which conducting compositions fire. While the following ideas are probably correct, some time will have to elapse before the theoretical work is complete and experiments are able to test detail. These views are, therefore, somewhat tentative and while based substantially upon the mechanism suggested by the H.E.C., elaboration is still in its early phases.

Any theory of c.c. action has to account for the following:-

(1) initiation in a few microseconds when using voltages as low as 12 and milliseconds with voltage as low as six.

(2) the existence of a voltage threshold.

(3) the possibility of an alternative mechanism which may give long firing intervals when the graphite content is high.

The particles in a conducting mix form a random array of contact resistance elements and these form circuits. At a branch point the total current contributed by several circuits will be higher than elsewhere and will cause a high temperature rise at that point. The hottest of these points is most likely to be the first to initiate the nearby explosive.

In the study of the mechanism of the very fast firing we are usually only interested in one junction; only the most active.

Once initiation has occurred, the behaviour at other current concentrations is assumed to be irrelevant. A slow firing mechanism is also possible in which all junctions gradually heat the explosive to a "cook off" temperature.

The theory of electric contacts shows that the temperature at the contact "neck" and the voltage drop across the bulk material in contact are related by:-

$$\frac{u^2}{8} = \int_{T_o}^{T} \rho k \, dT \quad \text{(ref. 4)}$$

where T = neck temperature

T_o = room temperature

ρ = electrical resistivity

k = thermal conductivity

u = voltage across the contacts

Figures 3 and 4 show data, from Holm's Electric Contacts Handbook, for the thermal conductivity and resistivity against temperature for graphite prepared at various temperatures.

Figure 5 shows the result of carrying out the integration of these data to give the temperature-voltage relationship for graphite. For graphite about 2 volts are required to produce a temperature of 500°C though this depends on the graphitisation temperature and the degree of anisotrophy of the graphite particles to some extent. For semiconductors such as silicon and manganese

dioxide values as high as 20 volts are required. For metals, temperatures as high as 500°C can arise from only $\frac{1}{4}$ of a volt.

Lead styphnate in contact with a temperature of 500°C requires only a small hot spot size for explosion and a mechanism for ignition in fast times is evident. For little increase in voltage a hot spot temperature of 1000°C or more is easily attained and the size of the contacts are such that the temperatures are in equilibrium in under a microsecond. Most explosives have explosion times which change from many seconds to a few microseconds according to the Arrenhius factor in the equations in a few tens of degrees centigrade (usually somewhere between 200 and 400°C).

The well known thermal explosion theory as collated by the Bowden school at Cambridge (ref. 5) gives the relationship:-

$$0.88 = \frac{Q}{K} \frac{E}{RTo^2} r^2 n A \exp\left\{\frac{-E}{(RTo)}\right\}$$

for the critical condition for the onset or decay of thermal explosion in a slab of homogeneous explosive.

For lead styphnate the thermochemical constants are:-

Q	heated reaction	880 calories per gram
K	thermal conductivity	4×10^{-4} calories/cm deg
E	activation energy	3.24×10^{-4} cals/mole
R	gas constant	1.99 cals/mole/°K
nA	activation frequency factor	10^{14} per second

Values of temperature for various slab thicknesses are as follows:-

To - Temperature °K	r - Slab thickness for critical condition
1000	1.6008×10^{-6} cms
900	3.782×10^{-6}
800	1.041×10^{-5}
700	3.899×10^{-5}
600	2.322×10^{-4}
500	2.918×10^{-3}
400	1.367×10^{-1}
300	9.607×10^{-1}

Hence a temperature of between 400°C and 500°C is required to explode a 26 micron slab. At higher temperatures the slab thickness decreases very rapidly and only thin surface layers of a particle of explosive would be involved in initiation.

This then, specifies the lowest stimulus under which explosion can occur i.e. good thermal contact between an explosive particle and the hot contact region between two conducting particles. 2 volts applied potential are required to produce the required temperature for a typical particle.

In the case we are considering however, it is sterically unlikely that there is pure thermal conduction between contact hot spot and explosive. A more likely elaboration involves the heating of the explosive by a fan of radiant energy, or by incandescent graphite vapour emitted from the hot contact outwards through the narrow wedge so that an area of an explosive crystal is heated.

The condition in the explosive in this case may be represented by the equation:-

$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial \chi^2} + \rho Q Z \exp(-E/RT) + Io\,\alpha\,\mathrm{Exp}(-\alpha\chi) \qquad 4$$

where T = temperature

t = time

ρ = density

c = specific heat

k = thermal conductivity

χ = distance

Q = heat release per unit mass of explosive

Z = frequency factor

E = activation energy

Io = radiation intensity

α = adsorption coefficient for the radiation

Now the onset of explosion is dependent upon the terms depending on heat conduction and heat received by radiation and mass transfer. Once the level exceeds a threshold beyond which the temperature starts to rise excessively, the explosive-energy-release term starts to make an overriding contribution and explosion occurs.

The radiant energy leads to direct heating, but a photothermal mechanism must also be considered i.e. absorption of light and its subsequent transformation into heat in the crystal lattice. The sensitivity of lead styphnate to ultra violet light is well known and may be demonstrated very easily by initiating lead styphnate with a photoflash bulb. All radiation received undoubtedly plays a part, though the strongest energy contribution is from the U.V. As we shall see from considerations below, incandescent transfer is probably the principal transfer mechanism involved. Pure photochemical initiation is ruled out since lead styphnate is not decomposed by continuous light of low intensity.

The high temperature in the region of the contacts changes very steeply and is confined to a region of the order of the contact area. Figures 6 and 7 shows data from a paper by Bowden and Greenwood on metal contacts. In electric contact theory, no account is taken of radiation losses since these are small compared with the thermal conduction terms. Radiation losses have been considered by Hopkins (Ziet. for Physik Bd. 147, S, 148-160-1957) and Cutler (J. Applied Physics. 32, 6, June, 1961) and the conclusion is that the temperature is virtually unaffected by the radiation loss. For the purposes of this paper we may consider that the temperatures may be estimated from contact theory and the radiation from the hot spot may be estimated as a fraction of the total dissipation in the following way.

Taking the contact radius as about 4 microns, the radiating area may be taken as about πd^2 or $3.14 \times 8 \times 10^{-8}$ cms. (Figure 6 and Figure 7 show the localisation of the hot spot in data from ref. 4). Putting the temperature in $1000^{\circ}C$ units we have the radiated energy I, for a black body:-

$$I = 25 \times 10^{-8} \sigma \times \left(\frac{T}{1000}\right)^4 \times 1000^4$$

$$= 34.4 \times 10^{-8} \times \left(\frac{T}{1000}\right)^4 \text{ cals/sec.} \qquad 5$$

The power in a contact of resistance R and having a voltage v is $\frac{v^2}{R}$;

Approximately $T = \frac{1}{2} \times 10^2 v^2$ so that the ratio of emitted radiation to dissipation is

$$\frac{34.4 \times 10^{-8} \left(\frac{I}{1000}\right)^4}{2 \times 10^{-2} T/R}$$

R is of the order 1-100 Ω and T 0-3000°C so that at the most this ratio could be

$\frac{34.4 \times 10^{-8} \times 81}{2 \times 10^{-4} \times 3000}$, i.e. of the order 10^{-4}, thus establishing that very little energy is emitted as radiation, however considering the possibility further, the time involved in a radiation step in the initiation process can be estimated as follows:-

Taking a contact resistance of 100Ω and a current of 20 m.a. the power at the initial junction is of the order 40 milliwatts; of this as we saw above, about 40×10^{-4} milliwatts may be radiated from the contacts to the explosive. It is now necessary to make some assumption about the angle through which the power generated at the contacts is lost. Under a microscope the graphite has the appearance of lumps of coal and an angle of 15° between contacts would appear reasonable. For spherical particles 26μ in diameter the distance between hot spot and explosive is 19μ and the radiation from the contact falls on the wall of the explosive with an intensity

$$\frac{P}{2 \times 19 \tan \frac{15}{2}} \times \frac{1}{2 \pi \times 19 \times 10^{-8}}$$

Assuming P, the radiated power to be 40×10^{-7} watts we obtain 0.67 watts/sq. cm or 0.16 calories/sq. cm/second (See Fig. 8)

Taking the thermal constants of the explosive as:-

density, ρ = 2.1 grms/cc

specific heat, c = 0.3 calories/gm

conductivity, k = $3. \times 10^{-4}$ calories/sq. cm/deg C/cm.,

we may estimate the time for the wall of the explosive to reach explosion temperature.

This amounts to solving the previous explosion equation without the explosive term and regarding the explosive merely as a thermal switch. The solution to the equation is given as a carpet graph in figure 9. However, the absorption coefficient is not known. Assume it to be high to find the shortest possible time for explosion and the solution for this case is

$$T - To = \frac{2}{k/s} \frac{P}{\rho} \left(\frac{kt}{\pi}\right)^{\frac{1}{2}} \qquad 6$$

Taking the temperature rise 400°C we obtain

$$400 = \frac{2 \times .16}{3 \times 10^{-4}/2.1 \times 0.3} \left(\frac{3 \times 10^{-4} t}{\pi}\right)^{\frac{1}{2}}$$

or t = 1.4 seconds

It is clear that at 3000° with generous assumptions concerning radiation absorption and emission, short times are not possible unless the explosive is in physical contact with the graphite hot spot.

The above mechanism therefore explains the slow firings possible at intermediate voltages and also explains why conducting compositions do not fire below 4 volts in practice.

Let us consider further what happens if the voltage per contact is raised further. At about 4 volts per contact the carbon suddenly has to change phase and here there is a much more efficient method of heat transfer, namely by the explosion of a volatile mass of incandescent graphite at approximately 3800°C from the contact hot spot to the nearby explosive. If as little as $\frac{1}{10}$ of the power is transferred in this way, very short firing times will result since the temperatures on the explosive wall will be very high and explosion will initiate in a thickness of well under a micron.

At 18 volts per contact an arc can be formed and in this case the bulk of the energy release takes place in the gas phase. Here the heat transfer by radiation reaches flux levels adequate to give functioning in fractions of micro-seconds. It appears unlikely, however, that 18 volts is reached at many junctions, even with the service firing conditions of 45 volts across the electrodes, so that the most likely fast functioning mechanism is by disruption of the contacts and heat transfer by means of a mass of incandescent graphite vapour when any junction exceeds 4 volts potential drop.

Experimental evidence is that erratic times are observed with firing voltages between 7 and 16. Above 16 volts, the time is consistently short and is explained by the burning time from the electrode gap to the receiving ionisation probe between 16 and 7 volts times between 50μ sec and fractions of a second are found. Below 7 volts, no very short times are observed and the initiation process takes at least as long as the burning phase and many do not fire at all. Below 6 volts very few fire and the indications are that none would be expected to fire at 4 volts.

The conclusion is that although 2 volts could theoretically cause a "fire" the probability of obtaining all of the applied 2 volts across one pair of contacts and having the hot spot of the contacts in contact with the explosive is remote. Nevertheless, 2 volts must be considered the hazard level.

Over sixteen volts total the chances of having 4 volts across a pair of contacts becomes near certainty. Below 7 volts it becomes unlikely that 4 volts appear across a pair of contacts but long times occur due to the radiation heat transfer. Below 4 volts fast firing is impossible and long firing intervals due to radiation effects become very unlikely.

The second firing mechanism in which firings occur very reproducibly after tens of seconds is due to bulk heating of the powder mix under near iso-thermal conditions, and operates from about 2 volts onwards for the N8 but depends on its thermal surroundings. Obviously if perfect thermal isolation could be provided, the application of a very small voltage would eventually raise the explosive mixture to explosion temperature.

Returning to the model, the sensitivity may now be considered. Approximately, in the condenser discharges taking only a few microseconds, explosion or non-explosion depends upon a power input criterion to the critical particle contact and whether the radiation on to nearby explosive exceeds the threshold level. Suppose that a current, i, is required to obtain the necessary power from the contact carrying the maximum current concentration in the model, then a power i^2r, r being the contact resistance, is required. This power, i^2r ensures explosion. Now if the ratio of current in the critical contact to total current is η, then the total current through the whole net is $\frac{100\ i}{\eta}$ and the total power is $\frac{10^4\ i^2}{\eta^2}$ R where R is the resistance of the whole array.

$\frac{R}{\eta^2}$ is then a relative measure of the power required to ensure explosion. Taking the critical voltage as about two volts and the contact resistance as 100Ω, this is of the order 20 milliamps so that the factor 4 may be used to convert values of $\frac{R}{\eta^2}$ to watts to obtain order of magnitude estimates. The range 0.2 -4 watts compares favourably with those found in N8 igniters filled with various graphite percentages.

The slow initiation, usually several seconds, which may be observed in conducting compositions having high graphite contents and fired on low voltages are probably due to a macro interpretation of the thermal equation to the whole electrode area rather than one contact. In this case there are a great many paths - about one hundred times as many as for the more sensitive low graphite content device. The whole of the explosive in the electrode area is heated and the conduction time plays an important part. With this bulk heating the room temperature boundary recedes slowly into the explosive filling until conduction no longer gives the sufficient cooling at the electrode area, the hottest part. Explosion then follows in a longish, fairly reproducible time. Such devices will of course fire by the short time mechanism, given the required threshold voltage.

5. SENSITIVITY DISTRIBUTION

The sensitivity is log normally distributed. A χ^2 test gave 1.6 with five degrees of freedom in the case of a sample of 53 arrays of 40% conductor, indicating a satisfactory fit. (Fig. 10).

It is also clear that the standard deviation of the sensitivity, unlike that of resistance, is not significantly affected by graphite content - reproducibility in sensitivity unfortunately cannot be obtained by increasing the graphite content of c.c. devices.

Figure 19 shows the effect of electrode gap on the sensitivity. Unlike resistance, the sensitivity is not drastically affected by the electrode gap. In the figure the order of the sensitivity lines for the 400 x 7 and

400 x 8 are reversed. At present there are not sufficient results to justify any conclusions as to whether this is particularly significant. The standard deviation on a log scale is about 0.15 so the standard error of the mean is $\frac{0.15}{\sqrt{10-1}}$ or 0.05 on a sample of 10 leading to a standard error of 1.12 used in the geometric sense. Clearly the inversion cannot be judged significant on the present sample size.

If electrode gap changes are used to control the resistance, there will be a small but probably acceptable effect on sensitivity. Electrode gap variations may explain much of the resistance variability but appear to contribute rather less to the sensitivity variation.

6. SENSITIVITY-RESISTANCE

The logarithm of resistance and the logarithm of sensitivity are linearly related over a wide range of the curve. Departure from linearity occurs when the conductor content approaches 100% in the model. In the c.c. devices themselves however, sensitivity has little meaning for this condition. The model otherwise provides a good explanation of the resistance-sensitivity relationship. Figure 15 shows the effect of electrode width and percentage conductor and illustrates clearly the dependence of resistance and near independence of sensitivity upon electrode width at a fixed percentage conductor.

Taking the 53 runs at 40% conductor the regression line which fits the scattered plots of $\log R - \log \frac{R}{\eta^2}$ is

$$\log \frac{R}{\eta^2} = 0.547 \log R + 0.439 \qquad 7$$

The correlation coefficient is - 0.634 which is highly significant. This justifies the views of experimenters that the high resistance items in a given batch are the most sensitive and that groups used to investigate firing energies should be chosen to have similar resistance distributions.

The standard deviation of the points about the regression line is 0.164 and the standard error of the regression coefficient 0.093. This suggests that the firing energy can be predicted from resistance within a factor of $(\text{antilog } 0.164)^3$ or about 3.

7. EFFECT OF THE ELECTRODE GEOMETRY

7(a) Gap

The effects of electrode gap have been mentioned under resistance and sensitivity but are amplified here (Fig. 18, 19). The effects on resistance are considerable since 400 x 9 at 40% conductor gives 500 while 400 x 5 reduces this to only 38; i.e. the resistance change is about six times the change in electrode gap.

7(b) Length

In the calculation carried out by digital and analogue computer, no direct calculations have been made on the effect of electrode length; however, it is possible to calculate the effect of putting the strips of 400 x 7 end to end. In this treatment, the interaction of the ends of the strips are neglected. In some cases paths might have existed due to interaction particles at the end of each strip. In the case of 40% conductor there are only a few paths in the whole 400 length and so the effect is not likely to be very serious.

Let the current efficiencies of the two strips be η_1 and η_2, the peak current concentrations $\overset{A}{I}_1$ and $\overset{A}{I}_2$ and total currents I_1 and I_2.

We have then

$$\eta = \frac{\overset{A}{I}_1}{I_1}, \qquad = \frac{\overset{A}{I}_2}{I_2} \qquad 8$$

$$\frac{\overset{A}{I}_1}{E} = \frac{\eta_1}{R_1} \qquad \frac{\overset{A}{I}_2}{E} = \frac{\eta_2}{R_2} \qquad 9$$

Thus for an applied potential E, we can find which of the strips, connected in parallel, has the highest current concentration by comparing $\frac{\eta}{R}$. Let this be the nth where n = 1 or 2. The overall resistance is $R_1 R_2/R_1 + R_2$ so that the total current, I is $E (R_1 + R_2)/R_1 R_2$. Denoting the parameters of the strip not carrying the maximum current concentration by a prime, the overall current efficiency is

$$\eta = \frac{\overset{A}{I}_n}{I} = \frac{\eta_n}{R_n} \frac{E R_n R'}{E(R_n + R')} = \frac{\eta_n R'}{R_n + R_1}, \qquad 10$$

where R' is the R_1 or R_2 remaining after the selection of $n = 1$ or 2. In this way η & R can be found for the compound strip and the resistance and sensitivity distributions found.

This was done, combining the 400 x 7 to form first 800 x 7 and then 1600 x 7, all at 40% conductor.

These calculations are summarised by the geometric means and standard deviations in Table 1.

TABLE 1

Effect of electrode length at 40% conductor

Array	No. of items	Gmr	GsdR	Gm $\frac{R_2}{\eta}$	gsd $\frac{R_2}{\eta}$
400 x 7	50	195	1.54	0.165	1.60
800 x 7	25	76	1.36	0.270	1.45
1600 x 7	12	37	1.25	0.500	1.48

The question now arises; is the reduced geometric standard deviation of resistance, obtained by increasing electrode length, lower than would have been achieved by increasing the graphite content but keeping the electrode length constant? (The alternative schemes having the same final resistance).

Plotting log R against σ_R leads to an approximate straight line which shows that the gsd(R) depends upon R only and is not affected by whether R is varied by changing the graphite content or the electrode length.

There does not appear to be any significant effect on the sensitivity spread as the electrode length is changed.

Changing the electrode length does not give a means of changing the spread in resistance or sensitivity.

The physical explanation of the independence of gsd(R) at constant R would seem to lie in the fact that there are relatively few conducting paths in the whole array. Doubling the length approximately halves the resistance by doubling the number of paths. The resistance may be lowered similarly by doubling the number of paths in the shorter electrode length - the conclusion is that the paths are similar in structure.

The following theory may also be applied to the effect of electrode length.

Let R_1 be the resistance of one particle system and R_2 that of another. Let the standard deviations of the resistances by σ_1 and σ_2. Then the overall resistance R is

$$R = R_1 R_2/(R_1 + R_2) \qquad 11$$

and the standard deviation of R may be found from:-

$$\sigma_R^2 = \left(\frac{\partial R}{\partial R_1}\right)^2 \sigma_{R_1}^2 + \left(\frac{\partial R}{\partial R_2}\right)^2 \sigma_{R_2}^2 , \qquad 12$$

using the additive property of the components of variance, and assuming R_1 and R_2 are not correlated

$$\text{thus} \quad \sigma_R^2 = \frac{R_2^4 \, \sigma_{R_1}^2 + R_1^4 \, \sigma_{R_2}^2}{(R_1 + R_2)^4} \qquad 13$$

now if R_1 and R_2 are equal and $\sigma_{R_1} = \sigma_{R_2}$ we have

$$R = R'/2 \qquad 14$$

$$\text{and} \quad \sigma^2_R = \frac{\sigma^2_{R_1}}{8} \qquad 15$$

i.e. halving R decreases σ_R by $\frac{1}{2\sqrt{2}}$

The foregoing applies to any distribution of R but is most meaningful if R is normally distributed. In the case of a log-normally distributed resistance (as is usually the case with conducting composition) we may find a relationship between the variance of the conductance and the variance of log R.

Putting $y = \log R$, where y is now normally distributed, with say $\bar{y}$ and σ_y known we may write as before

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \qquad 17$$

However, putting $z = \frac{1}{R}$

$$\log z = - \log R = - y \qquad 18$$

hence Log z is normally distributed with mean $-\bar{y}$ and the same variance σ_y^2. Thus $\frac{1}{R}$ is also log normally distributed.

Changing back to the original variables gives

$$R = 10^y$$

$$\text{and} \quad \Delta R = 10^y \, \Delta y \qquad 19$$

$$\text{and} \quad \sigma_R^2 = 10^{2y} \, \sigma_y^2 = R^2 \, \sigma_y^2$$

$$\text{hence} \quad \sigma_R = R \, \sigma_{\log R} \qquad 20$$

hence the standard deviation of R increases with increasing R

8. STATISTICAL EFFECTS ARISING PURELY FROM SAMPLING

In generating the random strip used in the model, the percentage conductor will vary from the nominal value due to sampling effects. Some contribution is, therefore, made to the variation of resistance and firing energy, directly ascribable to sampling even from a "perfect mix".

In the case of 40% conductor the sample will have binomial distribution in which p, the probability of having a conducting particle is 0.4 n, the total number in the array is 400 x 7 or 2,800 and q = 1-p = 0.6.

The binomial distribution has mean np and standard deviation $\sqrt{npq}$. Thus we expect, on substitution, to have a standard deviation of 25.9 and a mean of 1120 conducting particles out of a total of 2,800 particles. Thus the percentage variation allowing a range of $\pm$ 3 sd would be $\frac{1198}{2800}$ to $\frac{1032}{2800}$ or 42.7% to 36.9%. This would shift the geometric mean resistance from 300 Ω to 100 Ω in the 400 x 7 array. This accounts for a proportion of the observed variance which gives a total spread ($\pm$ 3sd) of 900 Ω to 32 Ω at a nominal 40% conductor.

Total variance in log units	=	.0562 i.e. $\left(\text{s.d. } (\log_{10} R)\right)^2$
variance component due to %C	=	.0062
remainder due to random arrangement	=	.0508

Thus the remaining variance would give rise to a spread 810 Ω to 37 Ω. The component of variance due to variation of %C in the samples is small compared with the effects caused by the random arrangement of the conducting particles.

9. CONCLUSIONS

The mechanism suggested by the High Explosive Committee has been considered in detail and this leads to a safety criterion of 2 volts in the case of graphite devices. The means whereby energy is transformed from hot spots at contacts to the explosive has been considered and the theory extended. Steric factors and low levels of heat transfer by purely radiative mechanisms explain the reason for high practical thresholds of 4 volts. Above 4 volts, violent disruption of particle contacts at 3500°C gives an efficient mechanism for energy transfer and explains functioning times of a few microseconds.

This step in the initiation process appears to be of extreme importance and explains the discrepancy between the lowest possible value that is derived from the thermal contact case and the lowest values observed in practice. Transfer involving incandescent graphite vapour appears to be the critical step and some theoretical work on this would be of interest.

Formation of an arc does not seem necessary as an explanation of the short initiation times, though undoubtedly arcs could form under the service firing conditions and would give very fast functioning times.

The geometry of random arrays in the case of a simple rectangular model gives good reproduction of the distributions of resistance and sensitivity.

The electrode gap geometry would appear to be critical in the sense that any variations can cause a large dispersion in properties. A bias in gap size however, seems unimportant provided the resistance is adjusted by graphite content.

A discrepancy still exists between the percentage graphite required in a model and in the N8 igniter. Possible reasons for this are:-

1. Non-spherical particles have an enhanced co-ordination number,

2. The effect of three dimensions,

3. The graphite particles may have relatively strong mutual attraction thus giving a correlated rather than random distribution,

4. The particles in the N8 igniter are smaller and have a size distribution,

5. A small effect due to the differences in density between graphite and styphnate.

This aspect of the study still requires further consideration. All may have some accumulative influence.

10. SUGGESTIONS FOR FURTHER WORK

The emission of radiation from contacts should be calculated in more detail and the conditions under which graphite may be vaporised at contacts requires theoretical and practical study. Extension of the thermal explosion theory including the heat flux term is also considered worthwhile since this has not been studied fully previously.

In experimental work the possibility of using a graphite in the form of spheres should be investigated. These could be produced from resin droplets and would eliminate the effects of irregular particle shapes.

11. REFERENCES

1. Professor S.C. Redshaw, University of Birmingham. Resistance and current concentration properties of some Random Arrays of Equal resistances. War Office Contract Report. MG/147/04. Oct. 1962.

2. H.C. Hottel, Transient heat flow in organic materials exposed to high energy thermal radiation. Industrial and Engineering Chemistry Vo. 47 No. 6, 1136.

3. H. Gawlik and A. Cornish R.A.R.D.E. Report 2/65.

4. Bowden and Williamson Proc. Roy. Society, 1958 A, 246, 1 and 13.

5. Endeavour, October 1962.

6. Electric Contacts Handbook. Holm.

12. ACKNOWLEDGEMENTS

The author fully acknowledges the help of the H.E.C. working party in conducting compositions. A major contribution to the work was made by H.J.Gawlik and A. Cornish who carried out the specialised programming of the Amos digital computer to generate random arrays. The details of their work are issued as a separate report. Miss P.Wright carried out most of the computer runs. The network analysis was carried out by Professor S.C. Redshaw in his Civil Engineering Laboratory at the University of Birmingham and is reported in reference 1.

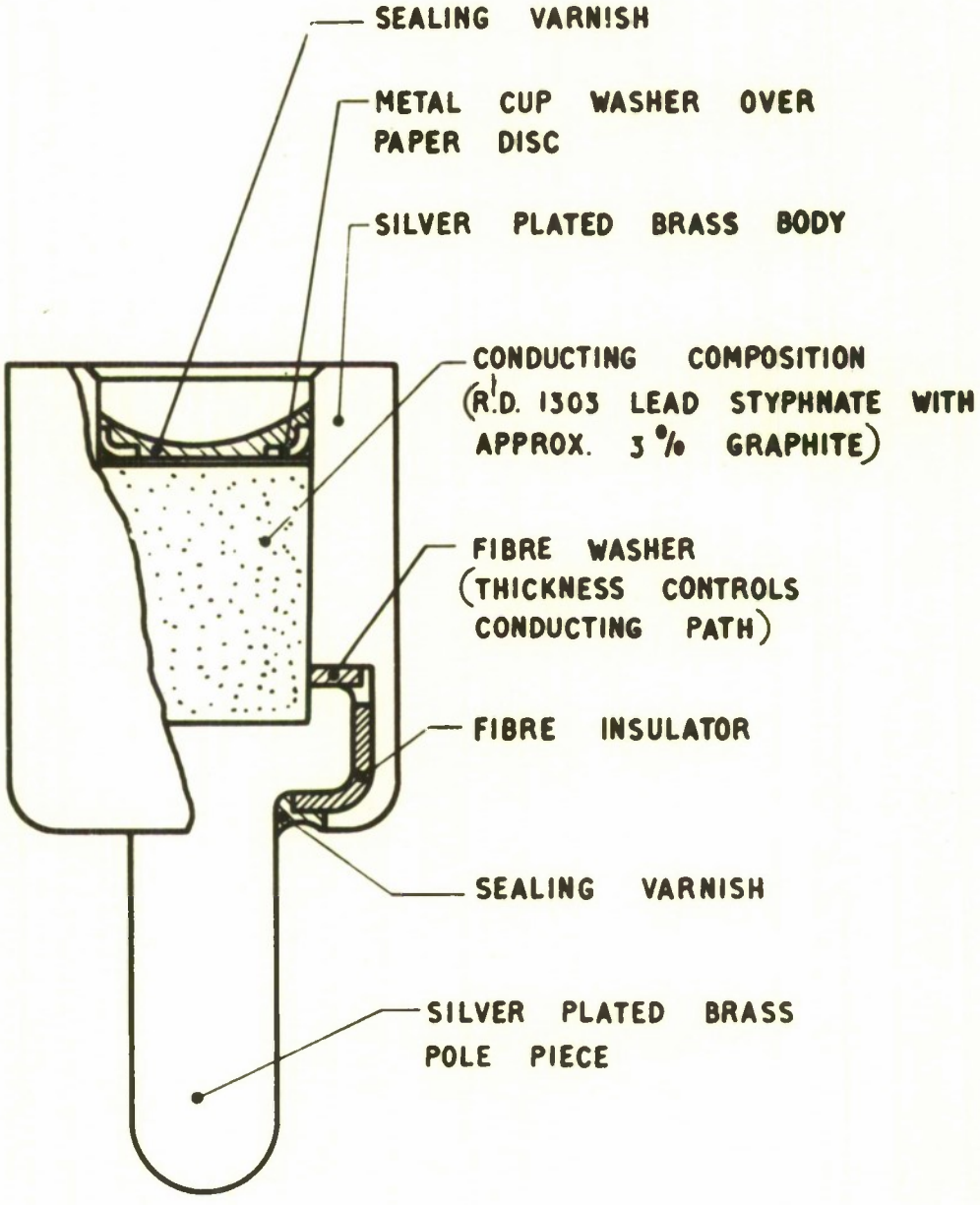


FIG. 1 MAIN FEATURES OF THE N.8 IGNITER

FIG. 2

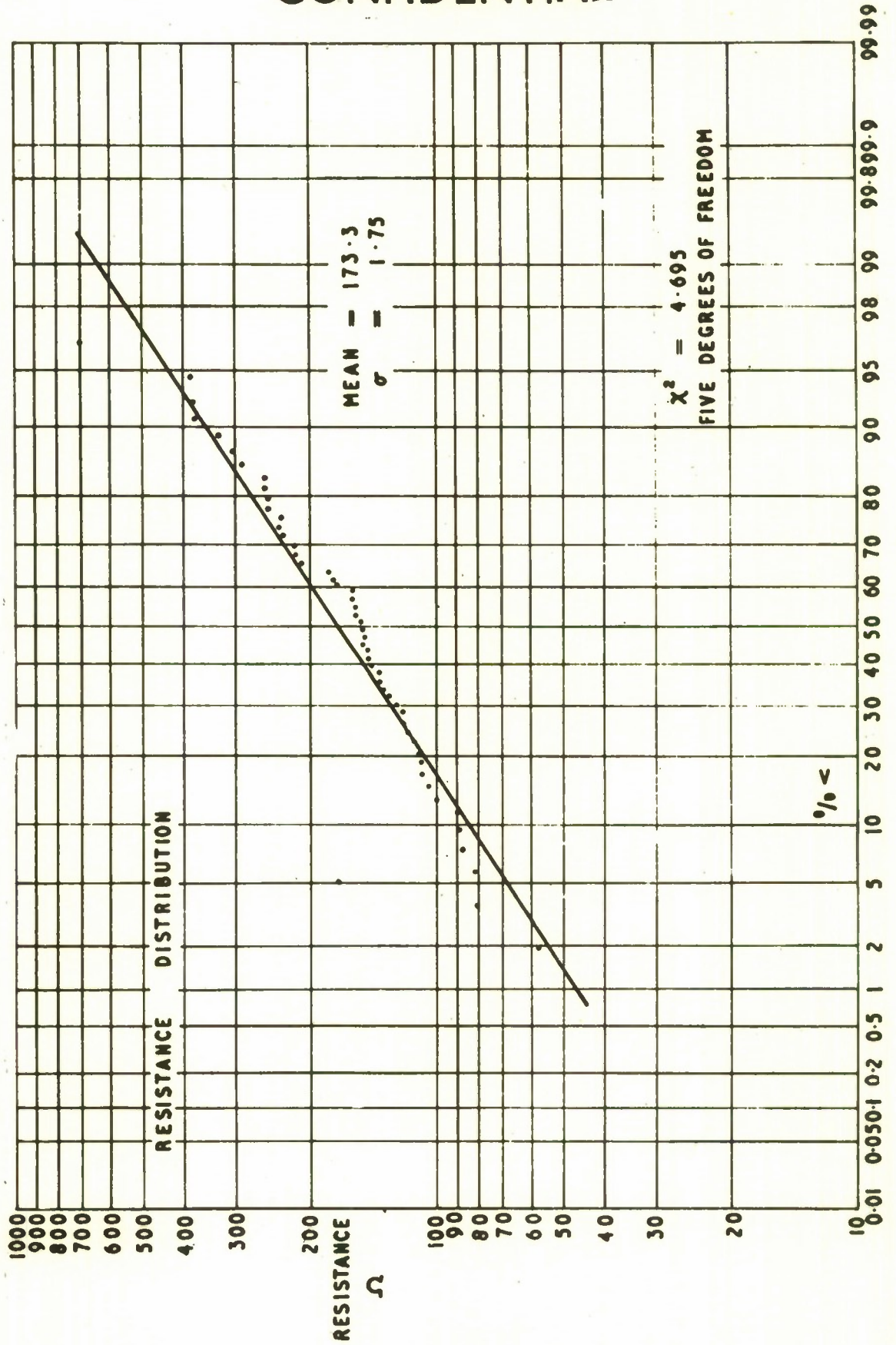


FIG. 2 MODEL 1 40 % CONDUCTOR 400 x 7
SAMPLE OF 53

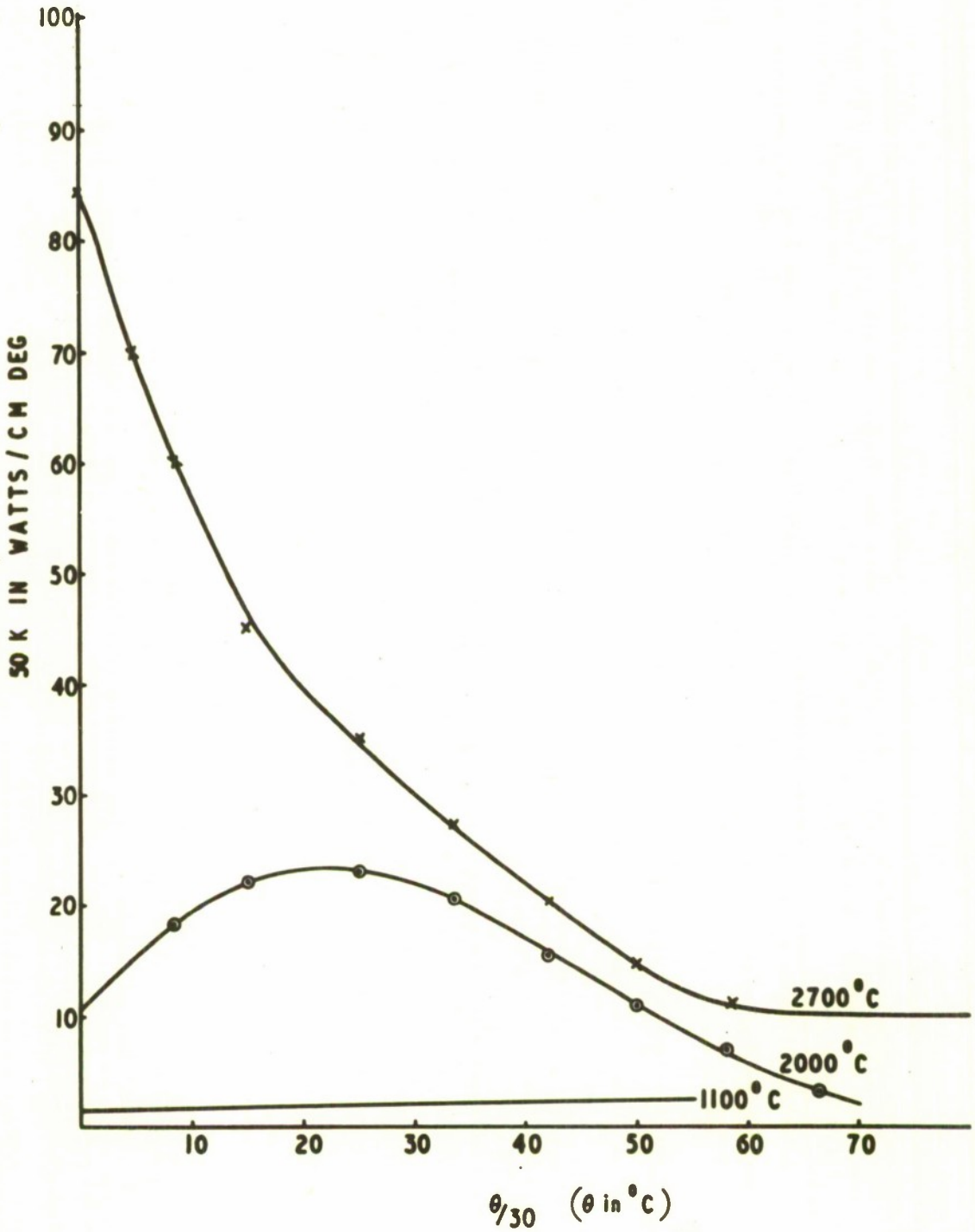


FIG. 3 THERMAL CONDUCTIVITY OF GRAPHITE PREPARED AT 2700, 2000, 1100 °C AGAINST TEMPERATURE

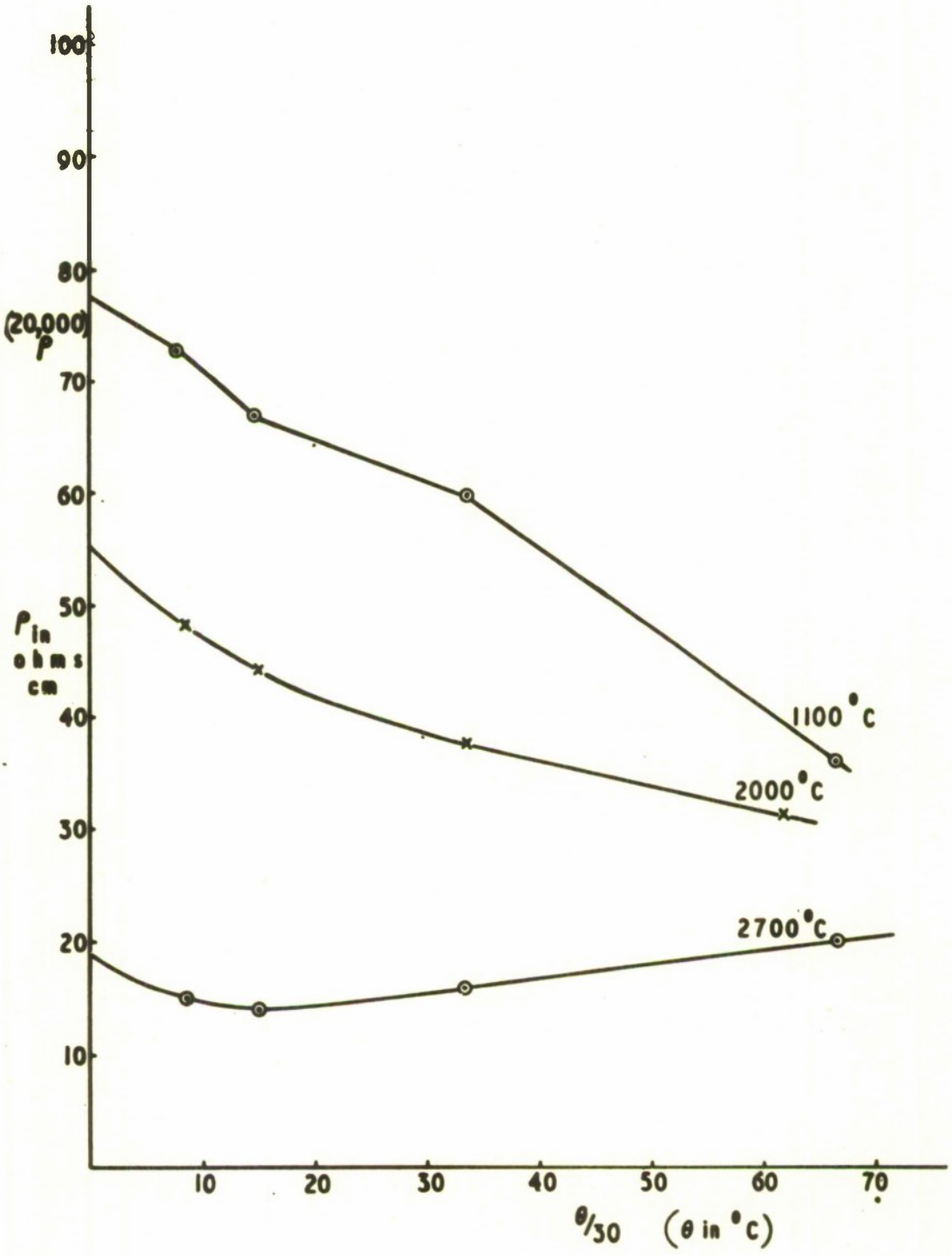
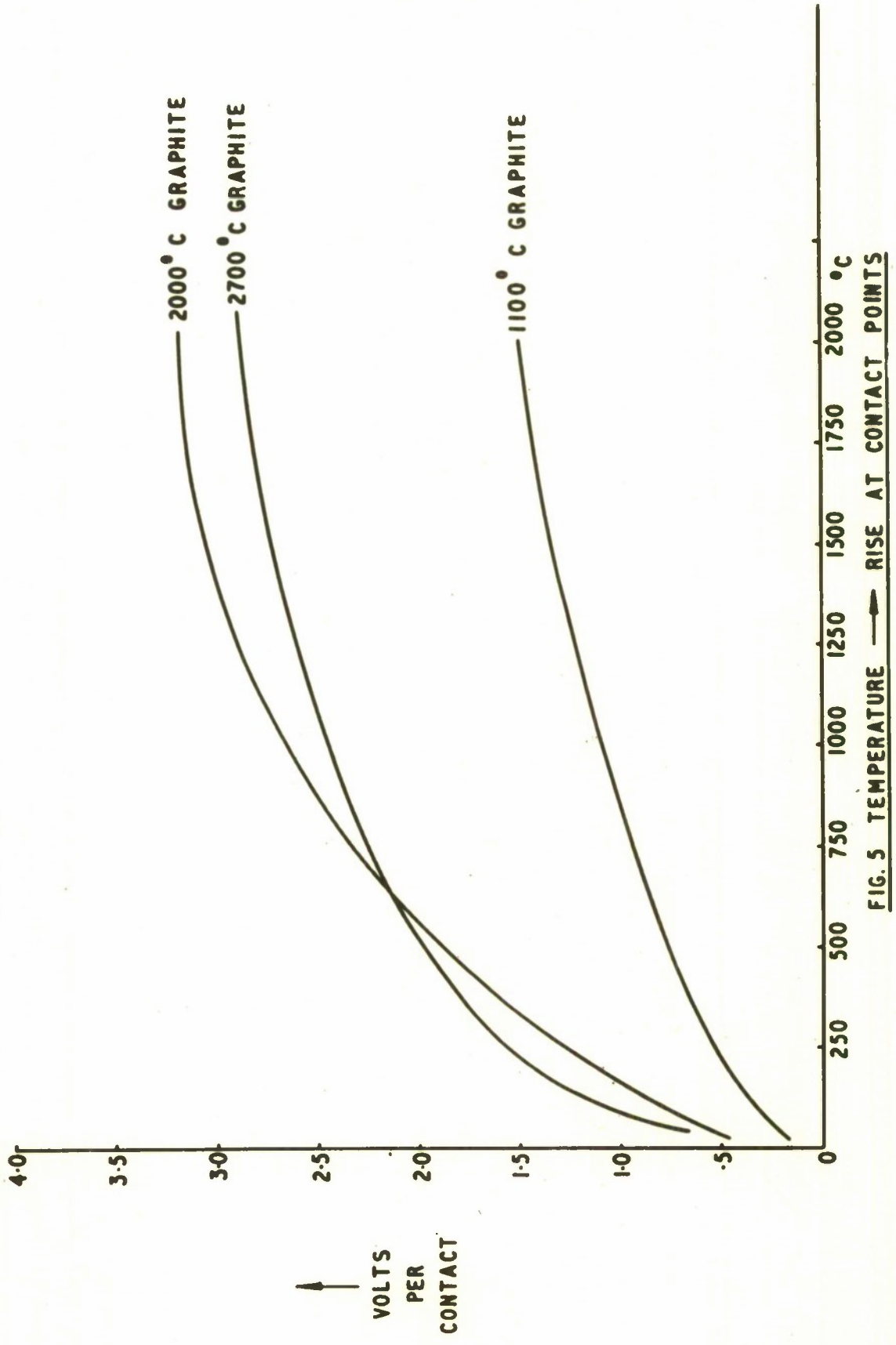


FIG. 4 RESISTANCE - TEMPERATURE FOR GRAPHITE PREPARED AT 2700°C, 2000°C, 1100°C

FIG. 5


2000° C GRAPHITE
2700 °C GRAPHITE
1100° C GRAPHITE
4·0
3·5
3·0
2·5
2·0
1·5
1·0
·5
0
250
500
750
1000
1250
1500
1750
2000 °c
VOLTS PER CONTACT
FIG. 5 TEMPERATURE — RISE AT CONTACT POINTS

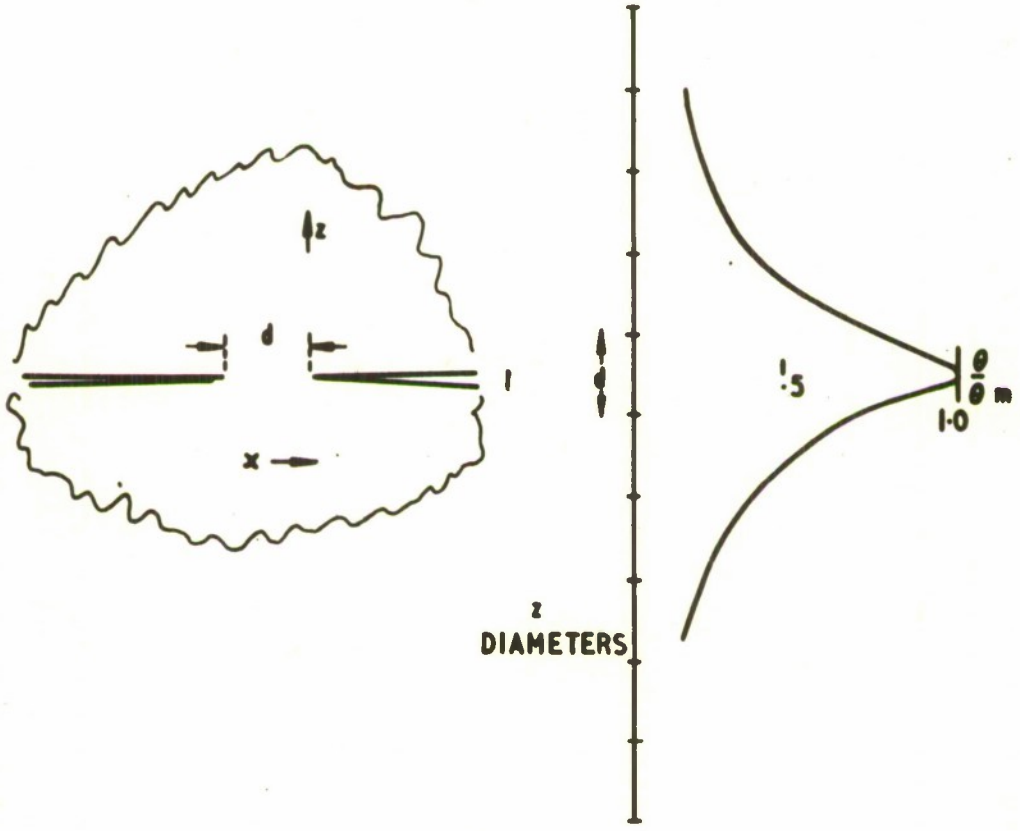


FIG. 6 TEMPERATURE DISTRIBUTION IN X = 0 PLANE OF AN ELECTRIC CONTACT HOT SPOT

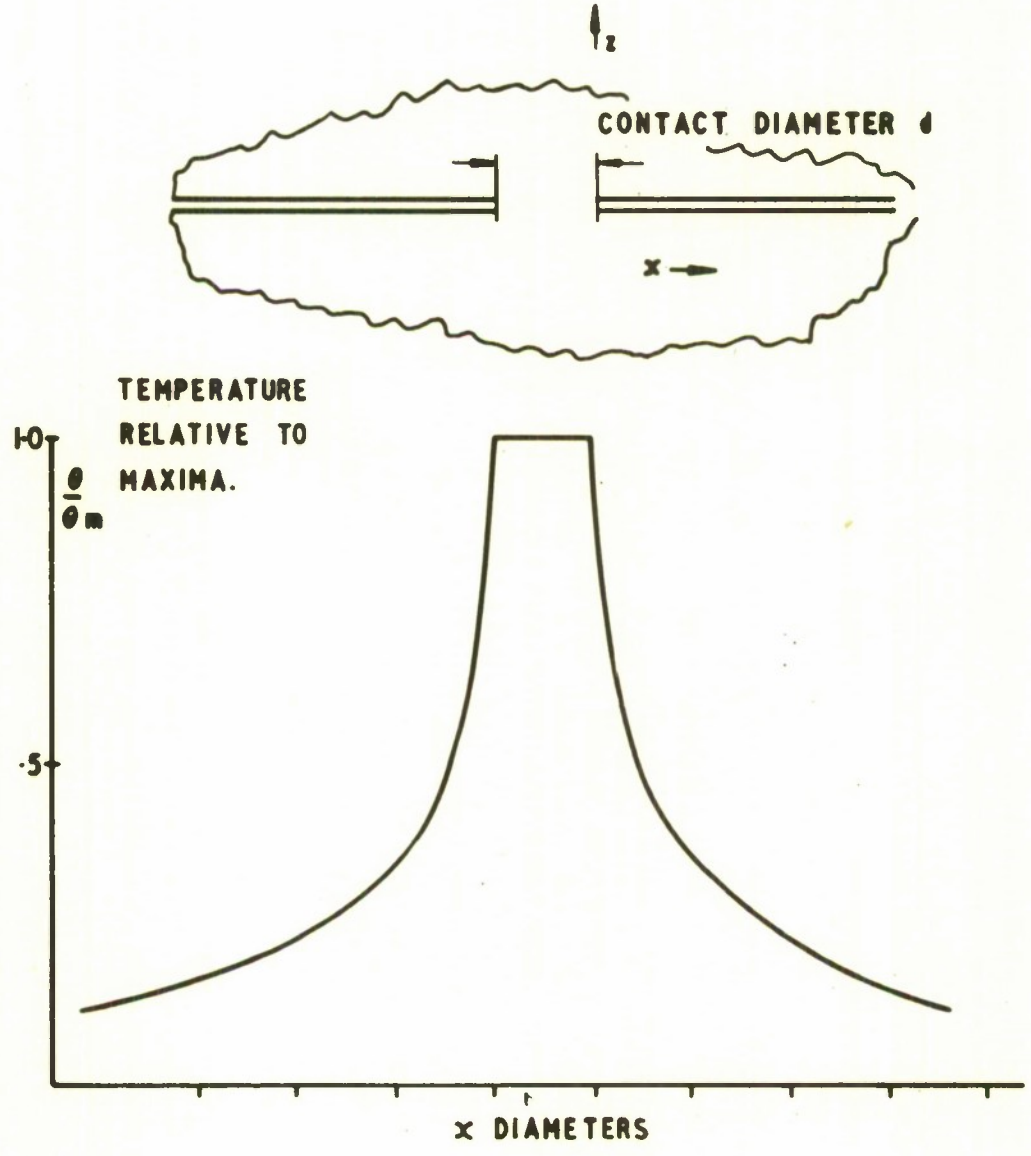


FIG. 7 TEMPERATURE DISTRIBUTION IN Z = 0 PLANE OF AN ELECTRIC CONTACT HOT SPOT

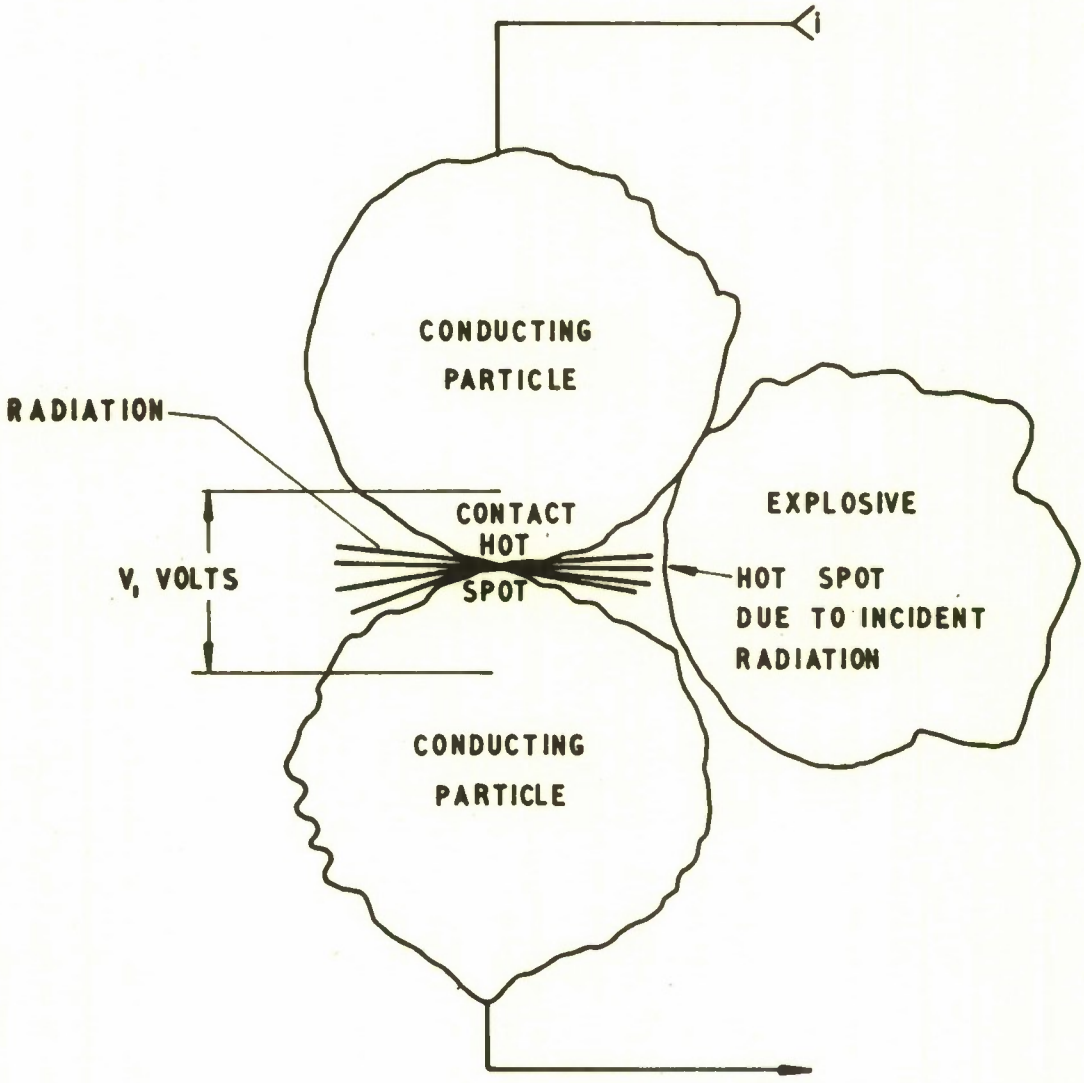


FIG. 8 MODEL USED IN THE DISCUSSION OF THE INITIATION OF AN EXPLOSIVE PARTICLE BY RADIATION FROM A HOT SPOT

FIG. 9

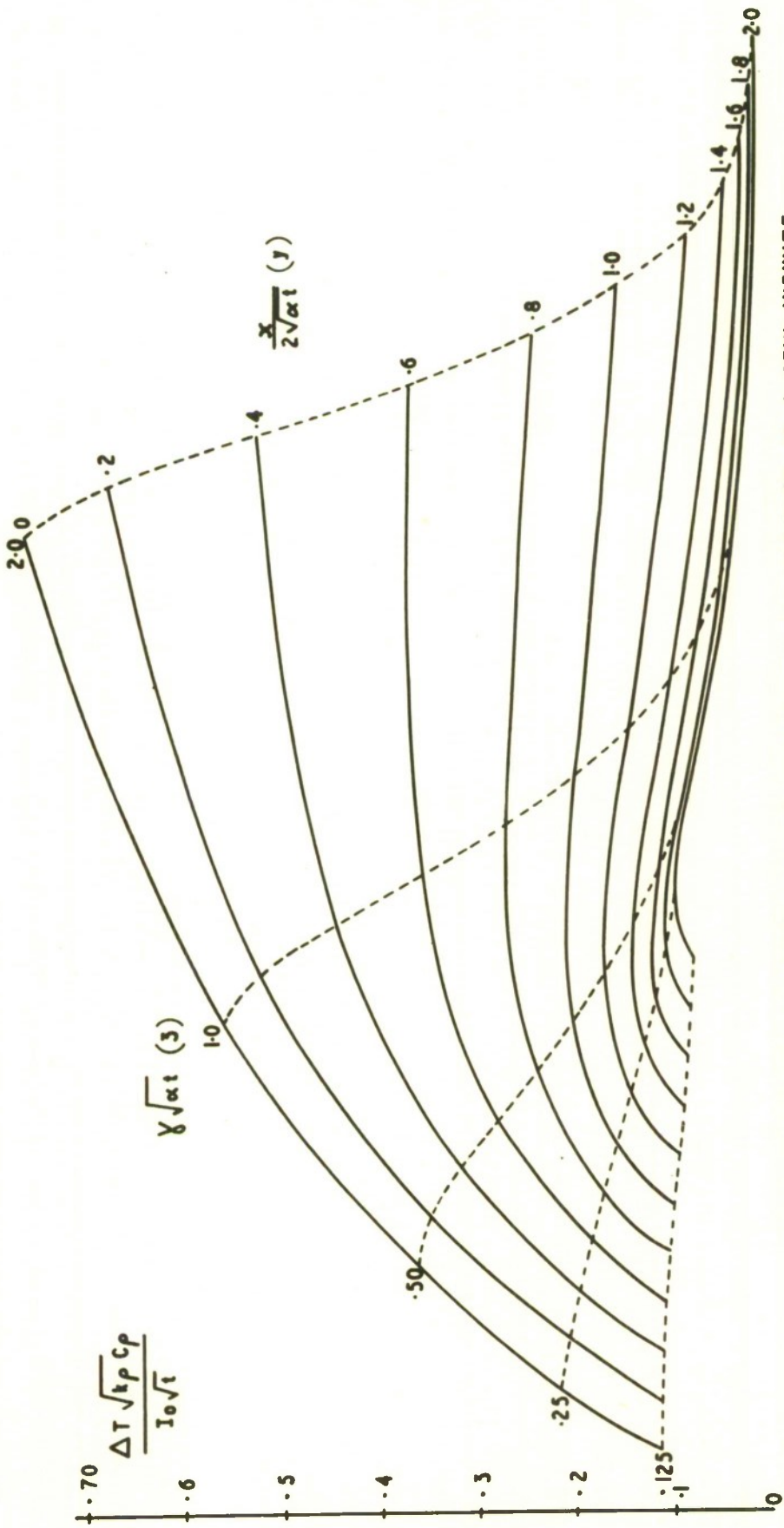


FIG.9 NORMALISED SOLUTION OF THE TEMPERATURE DISTRIBUTION IN A SEMI INFINITE SLAB HEATED BY RADIANT FLUX.

FIG. 10

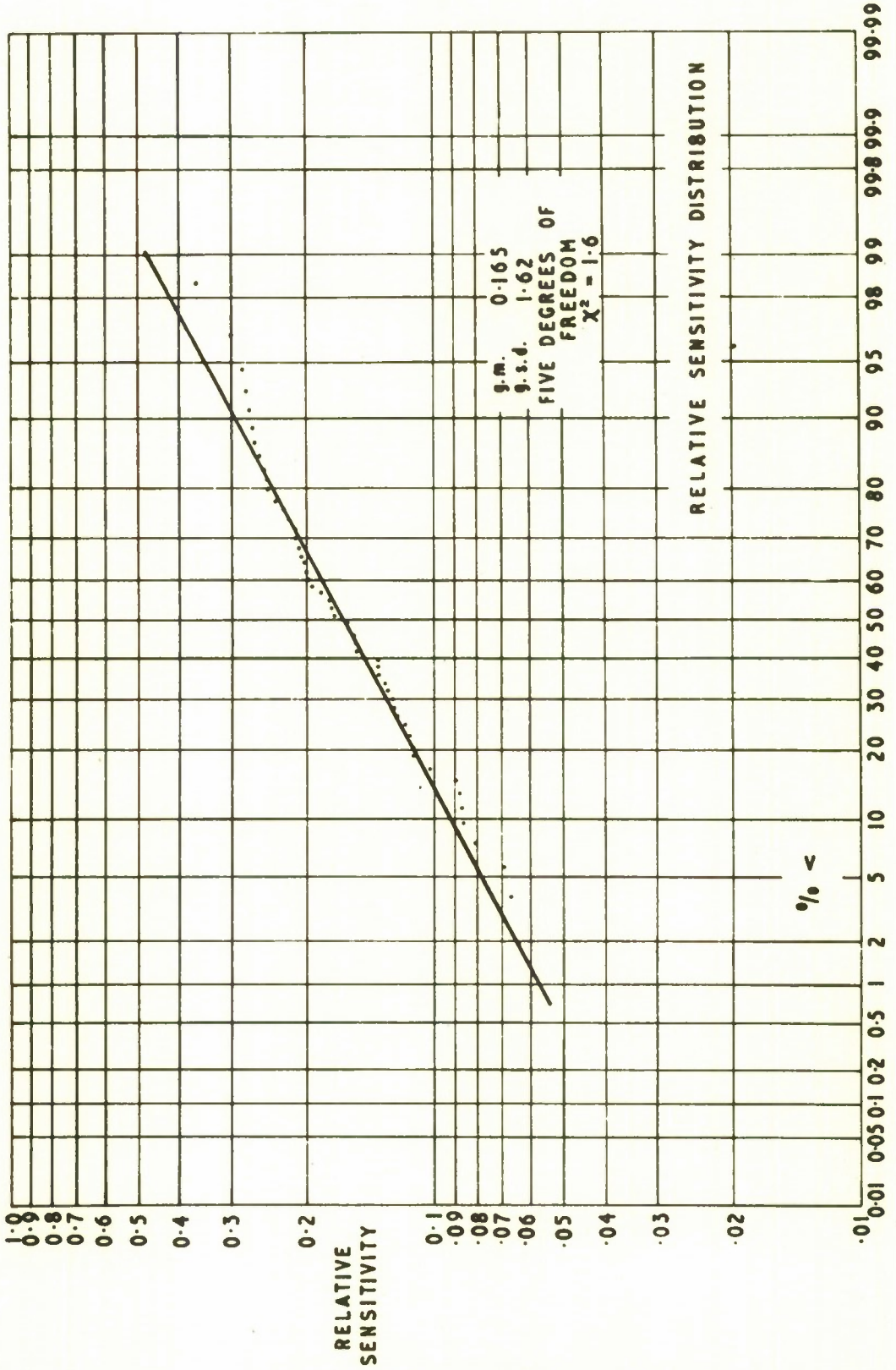


FIG. 10 MODEL 1 40 % CONDUCTOR SAMPLE OF 53

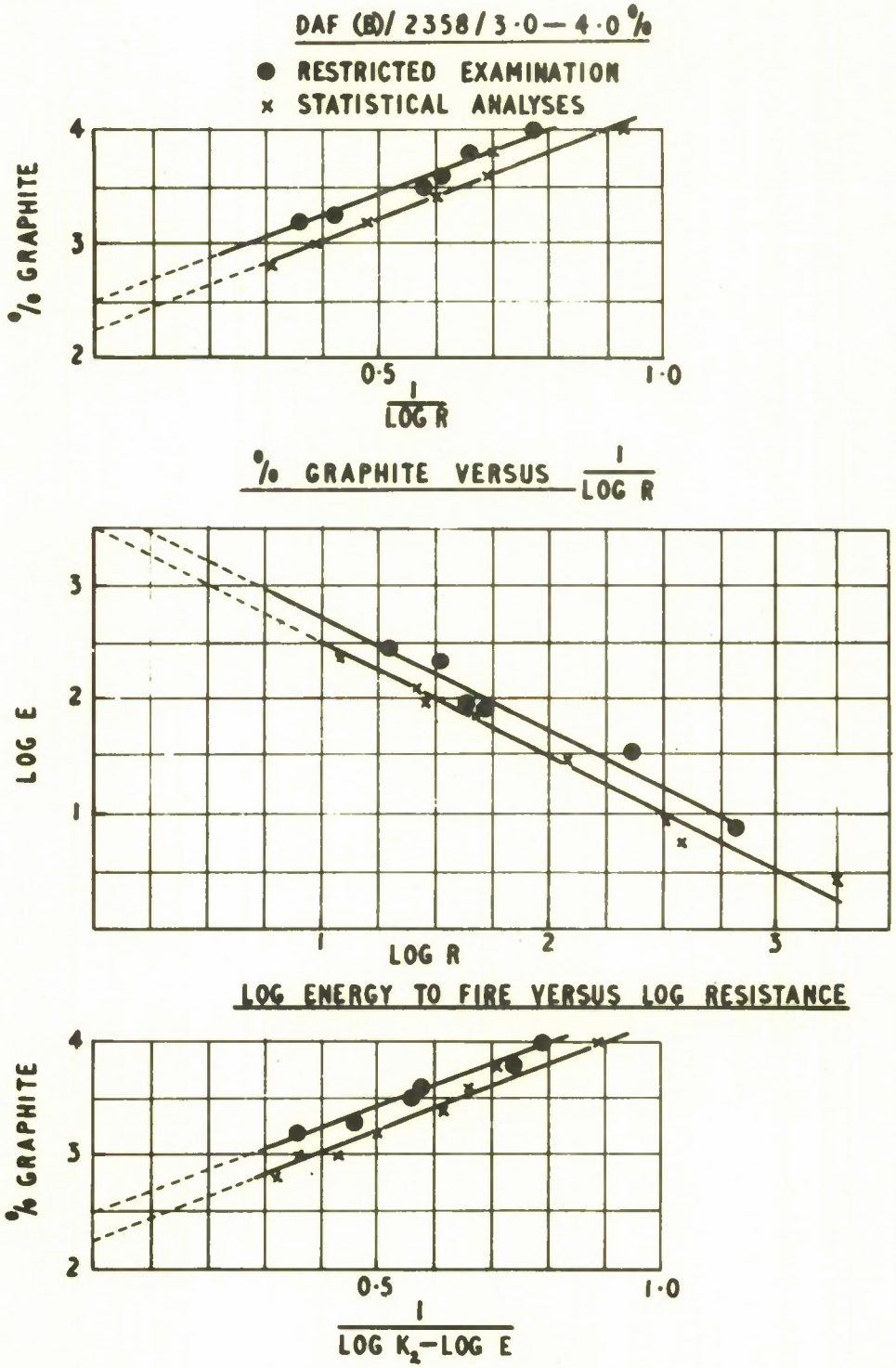


FIG. 11 RELATION OF PERCENTAGE GRAPHITE AND ENERGY REQUIRED TO FIRE AT 45 VOLTS

FIG. 12

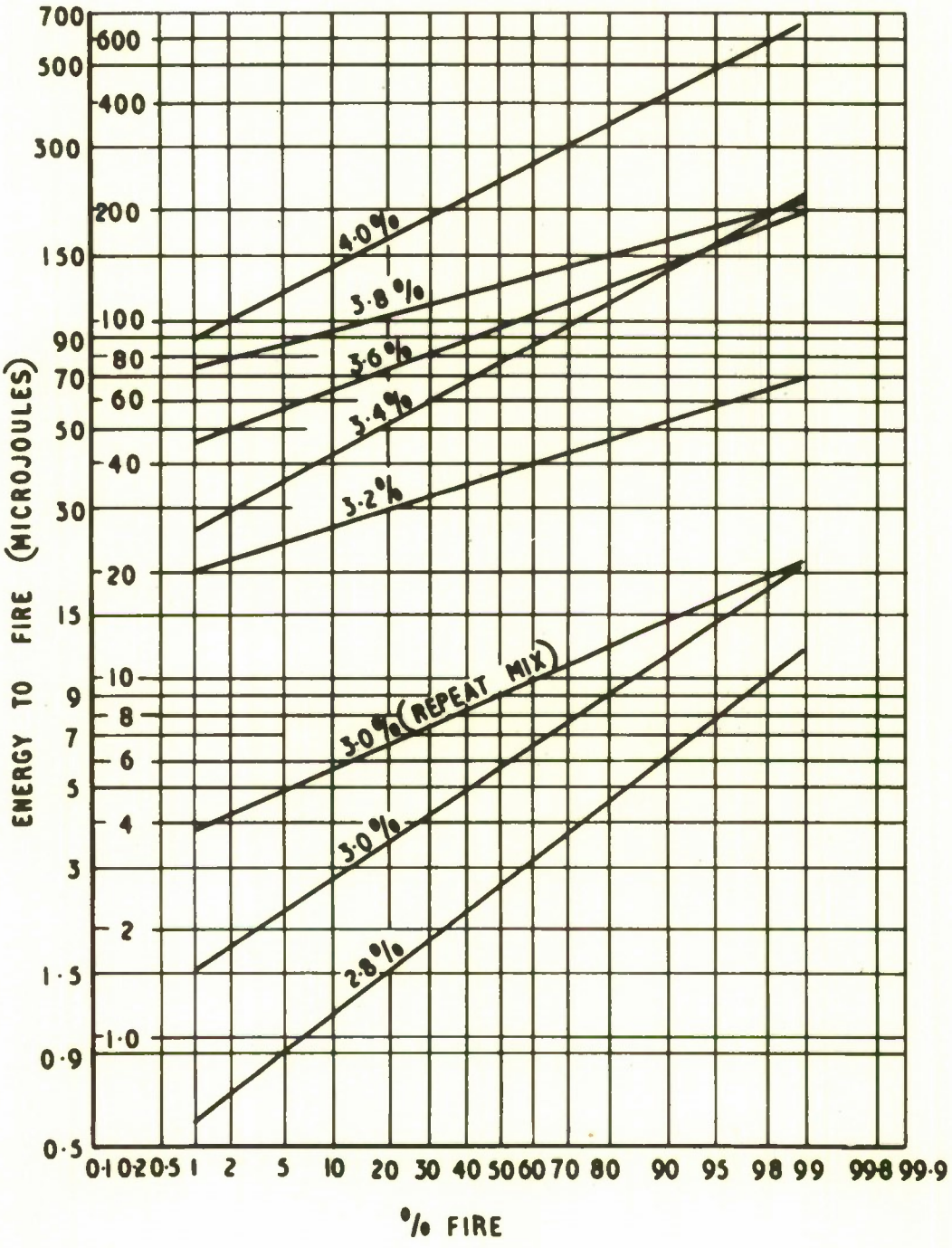


FIG. 12 MIXES OF FIG. 13
ENERGY DISTRIBUTION TO FIRE AT 45 VOLTS

FIG. 13

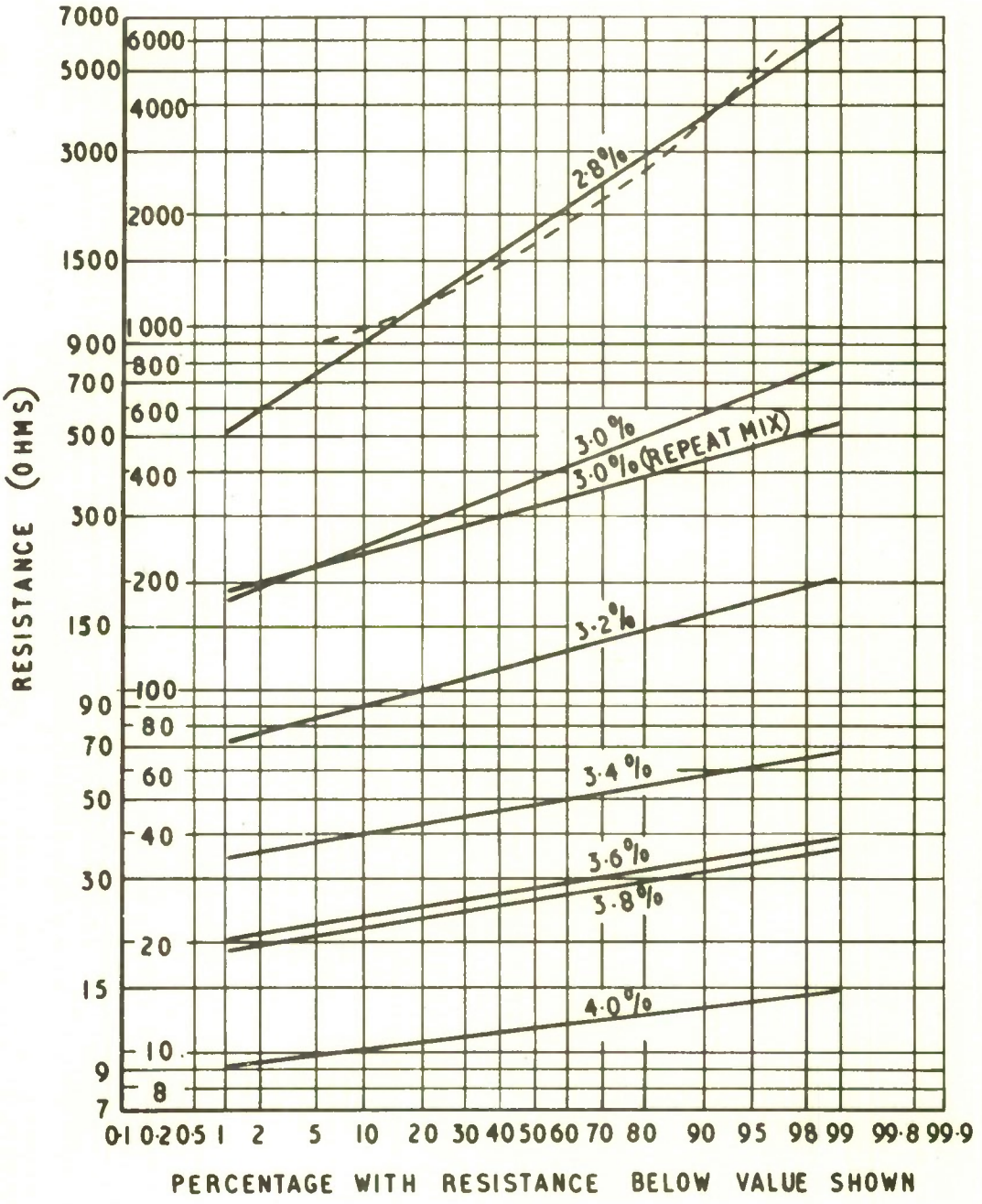


FIG. 13 AIR FLOATED GRAPHITE D A F (B) WITH RD 1303, BATCH 23/58
(JELLY MOULD MIXES MADE BY E. R. D. E., WOOLWICH)
RESISTANCE DISTRIBUTION.

FIG. 14

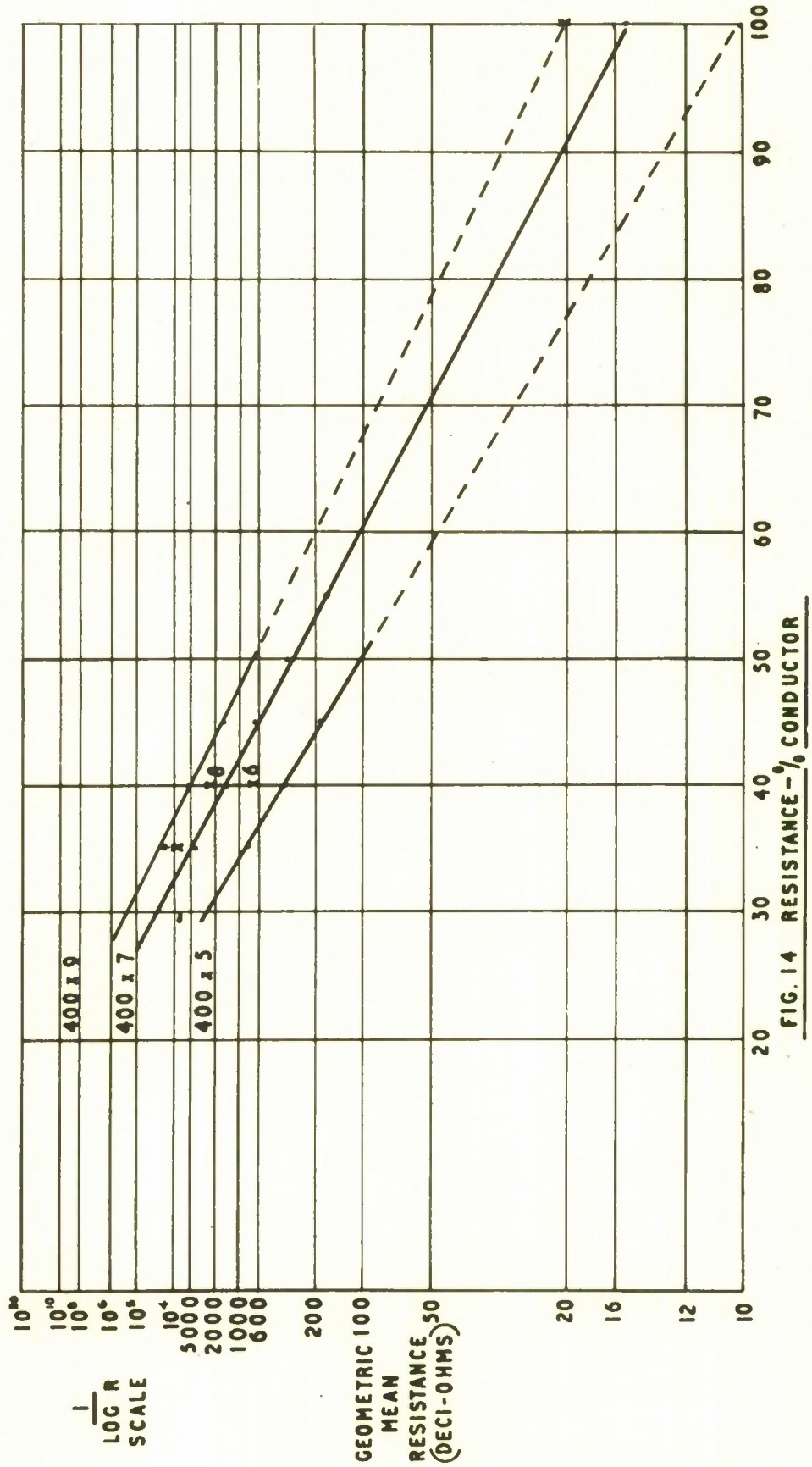

100
90
80
70
60
50
40
30
20
FIG. 14 RESISTANCE-% CONDUCTOR
400 x 9
400 x 7
400 x 5
10
16
10^{20}
10^{10}
10^{8}
10^{6}
10^{5}
10^{4}
5000
2000
1000
600
200
GEOMETRIC MEAN RESISTANCE (DECI-OHMS) 100
50
20
16
12
10
$\frac{1}{\text{LOG R}}$ SCALE

FIG. 15

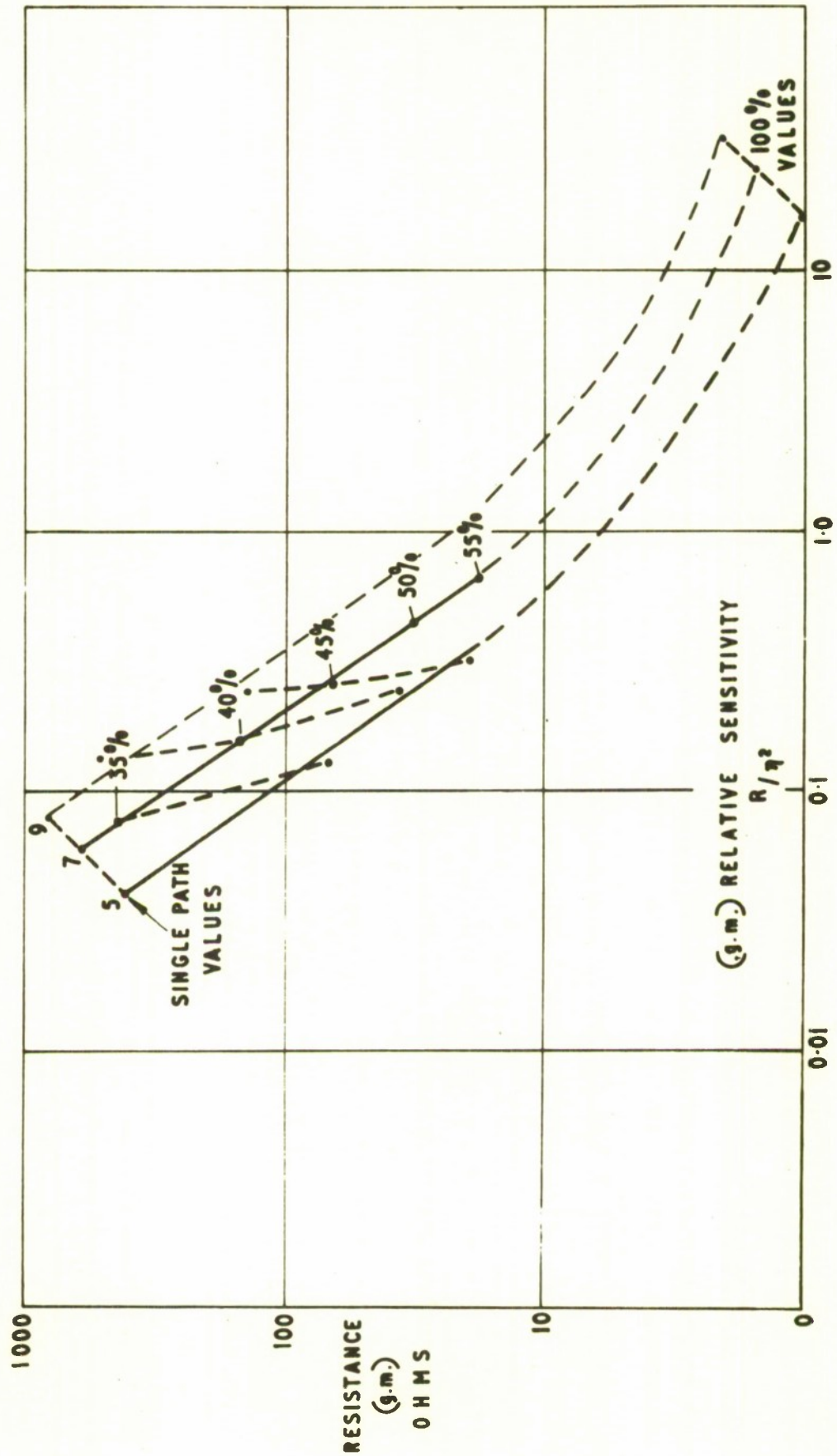


FIG.15 RESISTANCE - SENSITIVITY

FIG. 16

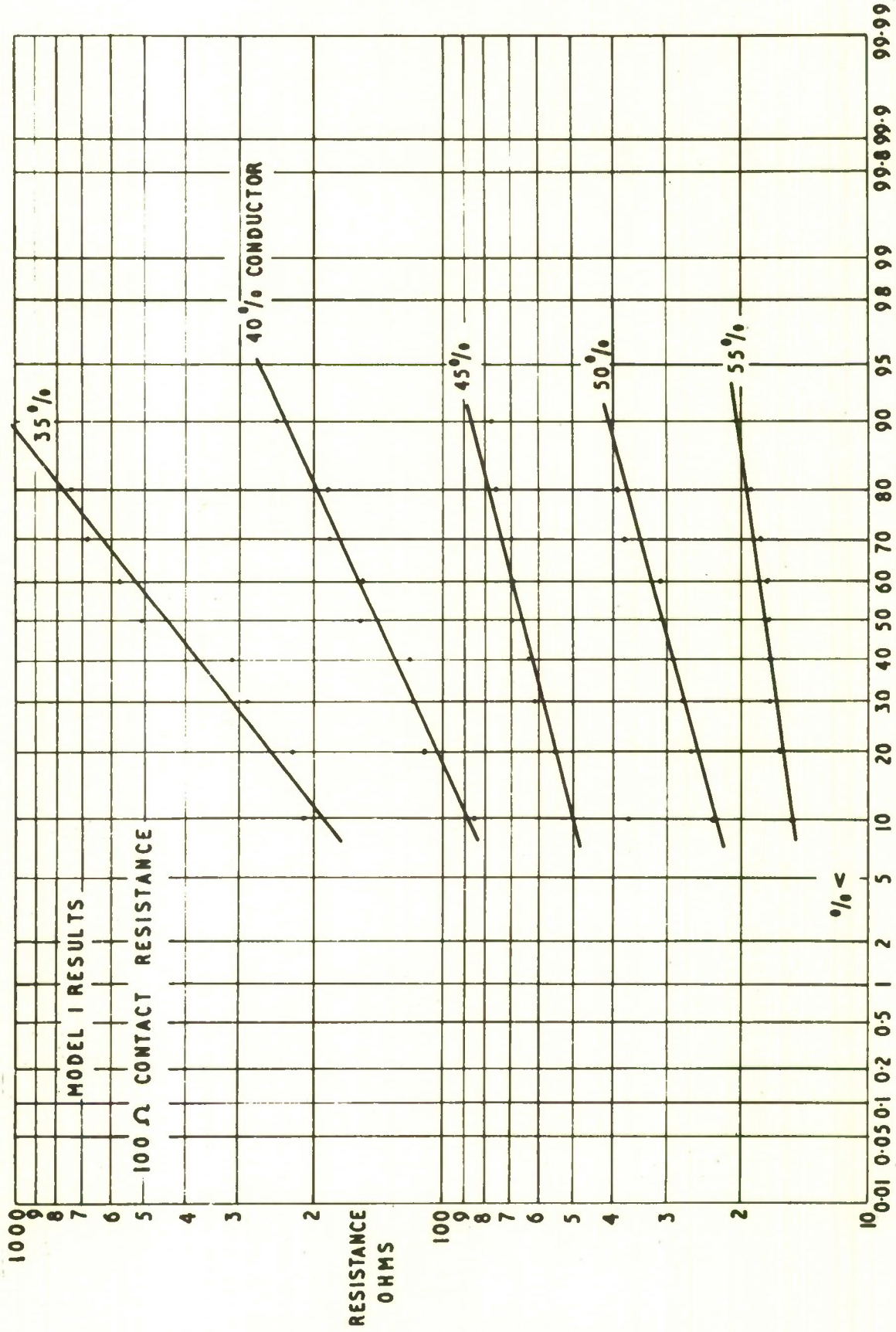


FIG. 16 RESISTANCE DISTRIBUTION (400 x 7)

FIG. 17

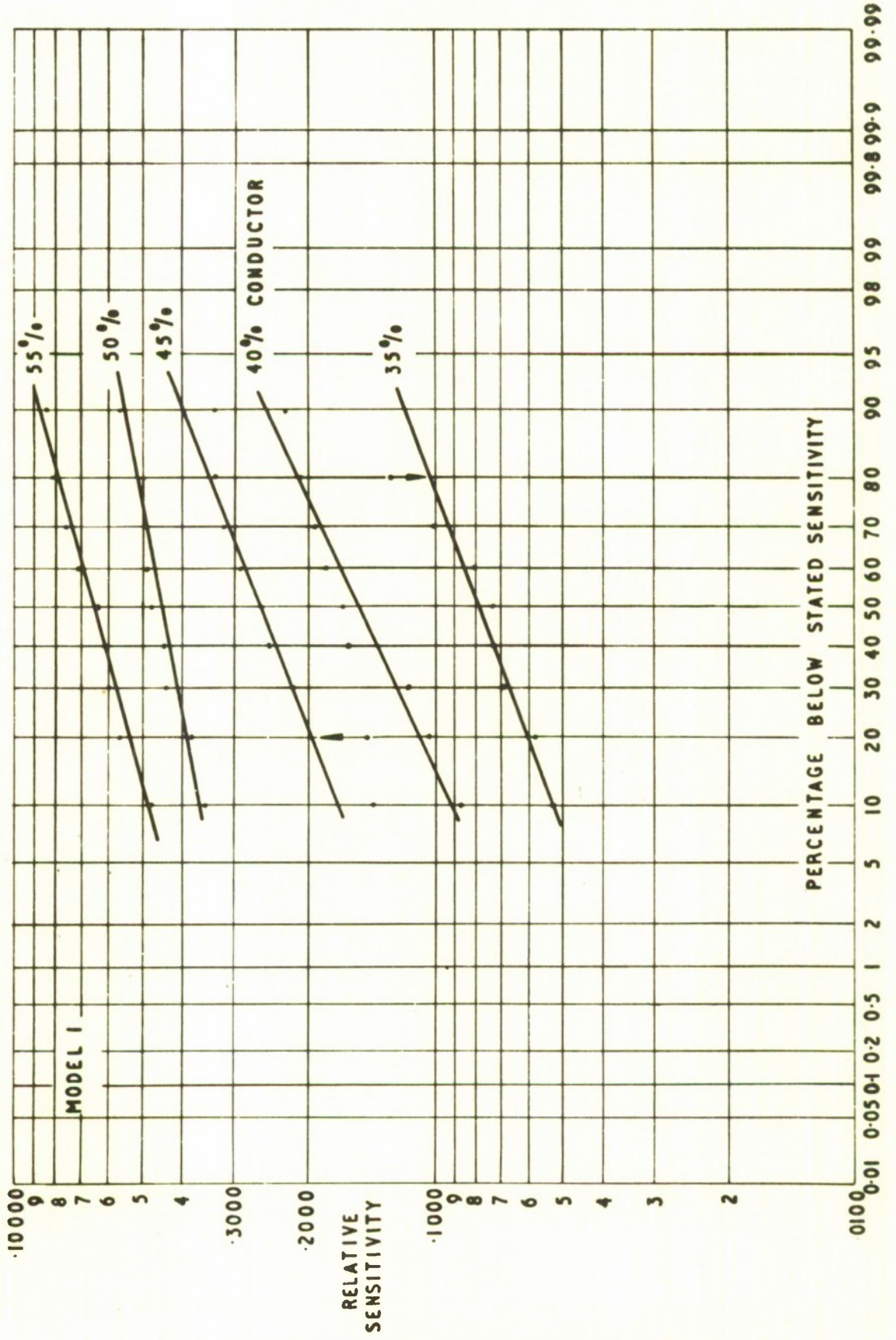


FIG. 17 SENSITIVITY DISTRIBUTION (400 x 7)

FIG. 18

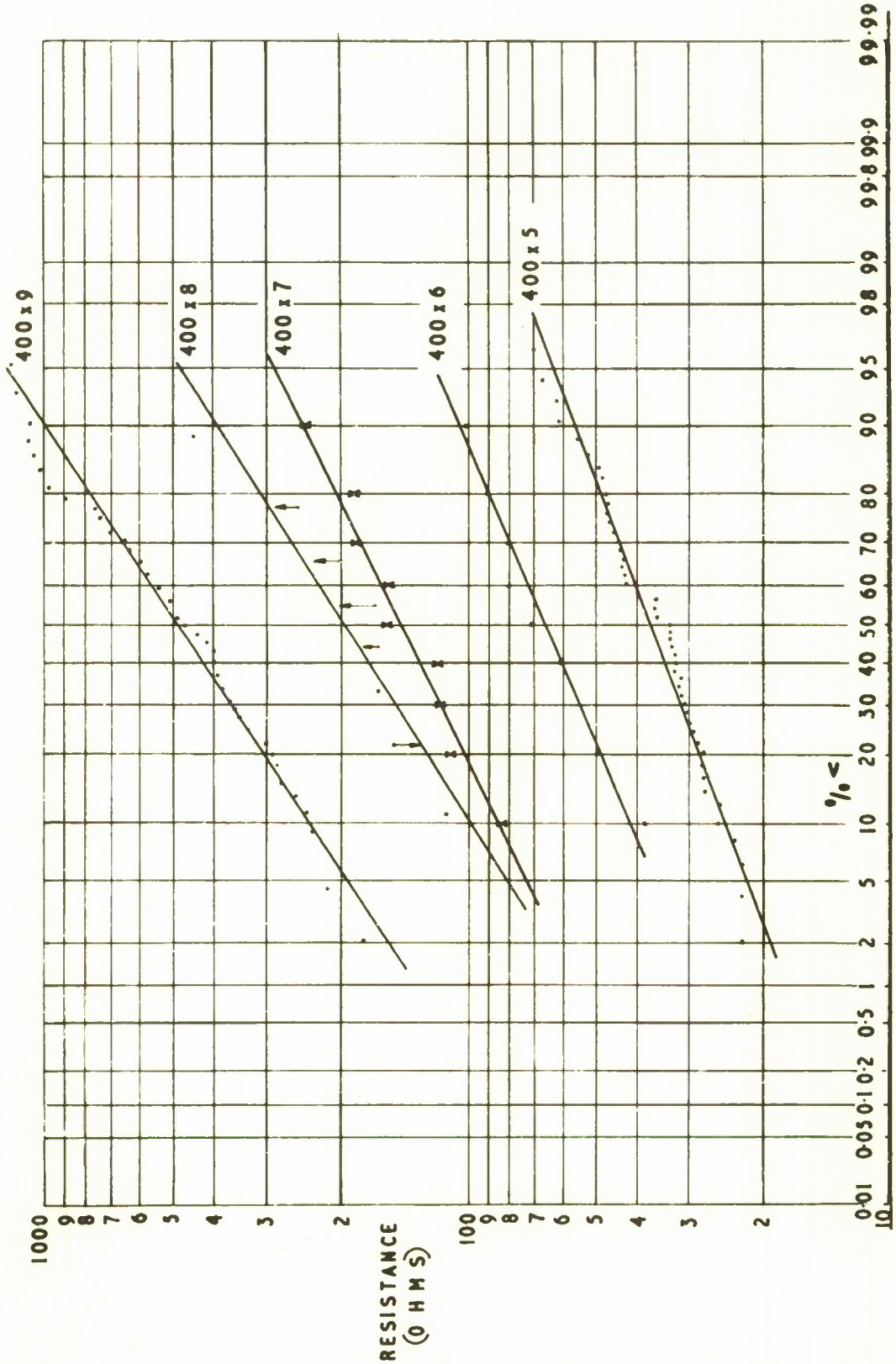


FIG. 18 EFFECT OF WIDTH AT 40% CONDUCTOR

FIG. 19

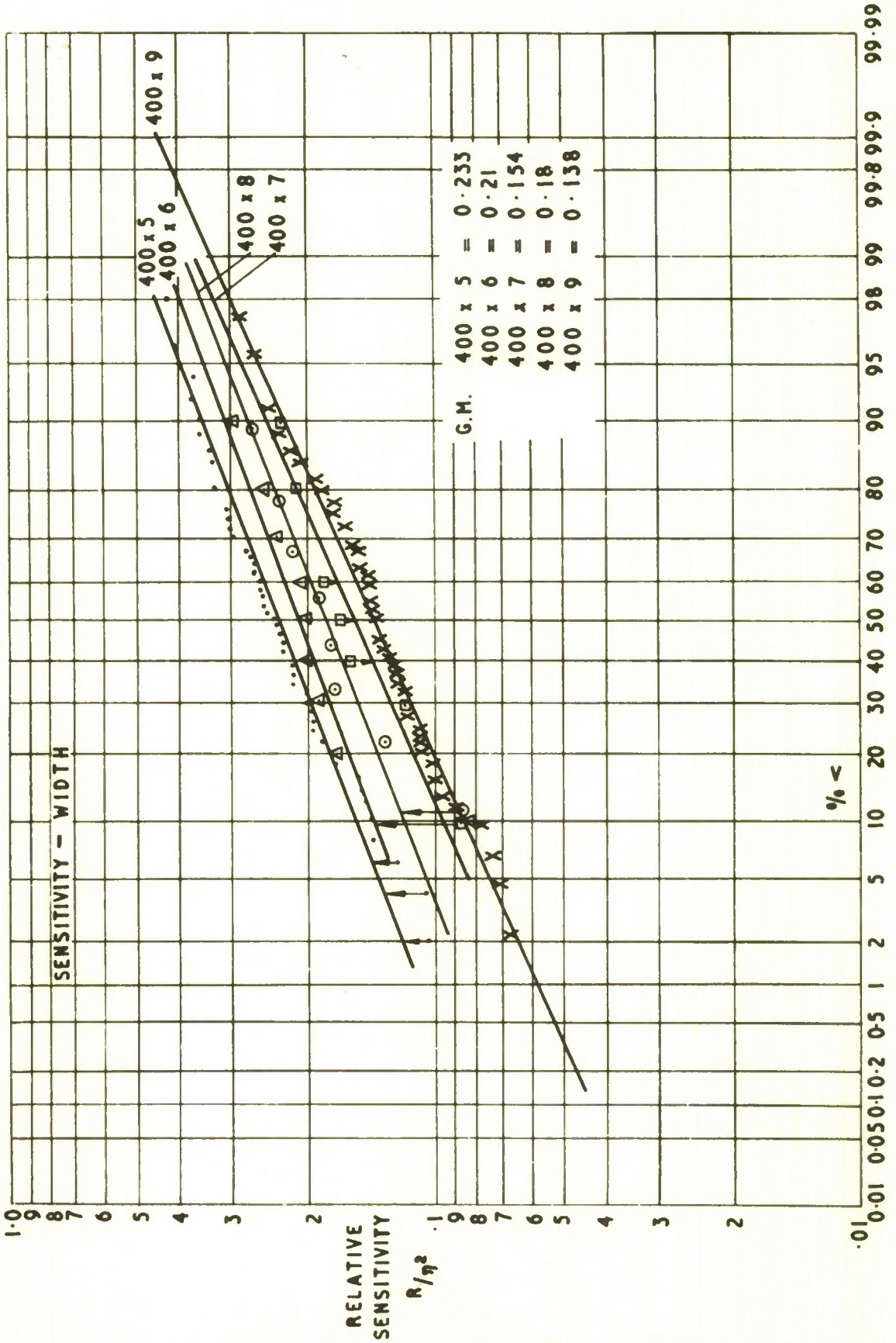


FIG. 19 EFFECT OF WIDTH AT 40 % CONDUCTOR

[dstl]

Information Centre
Knowledge Services
[dstl] *Porton Down,*
Salisbury
Wilts
SP4 0JQ
Tel: 01980-613753
Fax 01980-613970

Defense Technical Information Center (DTIC)
8725 John J. Kingman Road, Suit 0944
Fort Belvoir, VA 22060-6218
U.S.A.

AD#:
Date of Search: 12 December 2006

Record Summary:

Title: Physics and statistics of the electrical initiation process in conducting composition systems
Covering dates 1965
Availability Open Document, Open Description, Normal Closure before FOI Act: 30 years
Former reference (Department) MEMORANDUM 7/65
Held by The National Archives, Kew

This document is now available at the National Archives, Kew, Surrey, United Kingdom.

DTIC has checked the National Archives Catalogue website (http://www.nationalarchives.gov.uk) and found the document is available and releasable to the public.

Access to UK public records is governed by statute, namely the Public Records Act, 1958, and the Public Records Act, 1967.
The document has been released under the 30 year rule.
(The vast majority of records selected for permanent preservation are made available to the public when they are 30 years old. This is commonly referred to as the 30 year rule and was established by the Public Records Act of 1967).

This document may be treated as UNLIMITED.